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FINAL REPORT

MICROPROCESSOR REALIZATIONS OF RANGE RATE FILTERS

NAS 9-15347

Prepared for
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
JOHNSON SPACE CENTER
HOUSTON, TEXAS

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February 28, 1979

FINAL REPORT

MICROPROCESSOR REALIZATIONS OF RANGE RATE FILTERS

NAS 9-15347

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February 28, 1979

ABSTRACT

This report evaluates the performance of five digital range rate filters. A range rate filter receives an input of range data from a radar unit and produces an output of smoothed range data and its estimated derivative range rate.

A comparative study of the filters is made through simulation on an IBM 370. Two of the filter designs are also implemented on a 6800 microprocessor-based system.

Comparisons are made on the bases of noise variance reduction ratios and convergence times of the filters in response to simulated range signals.

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I. INTRODUCTION

The range rate filters discussed in this report are digital filters designed to accept a digitized input from navigational equipment, representing a range value, and to output a smoothed range value and its estimated derivative, range rate. Five filter designs are evaluated. Each is based on different design concepts; hence, the filters have widely varying capabilities.

The purpose of this report is to present a comparative study of the five digital range rate filters. With this in mind, a section detailing the theory of operation for each filter is provided. As a comparative study, the main objective is to present actual test data in such a manner that direct comparisons can be easily drawn between the widely varying filter types. Based on this data, conclusions are made as to filter performance in terms of variance reduction ratios, convergence times and ease of implementation.

The report is divided into two major sections -- full-scale computer simulations and microprocessor simulations. In the first section, the five filter designs are implemented on an IBM 370 computer. Given the higher precision available on a full-scale computer, these simulations represent best case results. Each filter is subjected to the same tests performed at two sampling rates: 2500 samples/second and 6.25 samples/second. The data is presented in tables for each filter.

From the information obtained from the full-scale computer simulations, two filter designs are chosen to be implemented on a microprocessor based system. The limitations on speed and word size imposed by the microprocessor require special attention be given to programming the filter algorithms. The resulting simulation data is presented along with equivalent IBM 370 simulation data for direct comparison.

II. DESCRIPTION OF FILTERS

A. Filter 1

Filter 1 is a digitized version of the continuous system described by the transfer functions

$$H_R(s) = \frac{RE}{RM} = \frac{sK1 + K2}{s^2 + sK1 + K2} \tag{1}$$

$$H_{RR}(s) = \frac{RDOT}{RM} = \frac{sK2}{s^2 + sK1 + K2} \tag{2}$$

for range and range rate, respectively. The block diagram for this analog system is shown below.

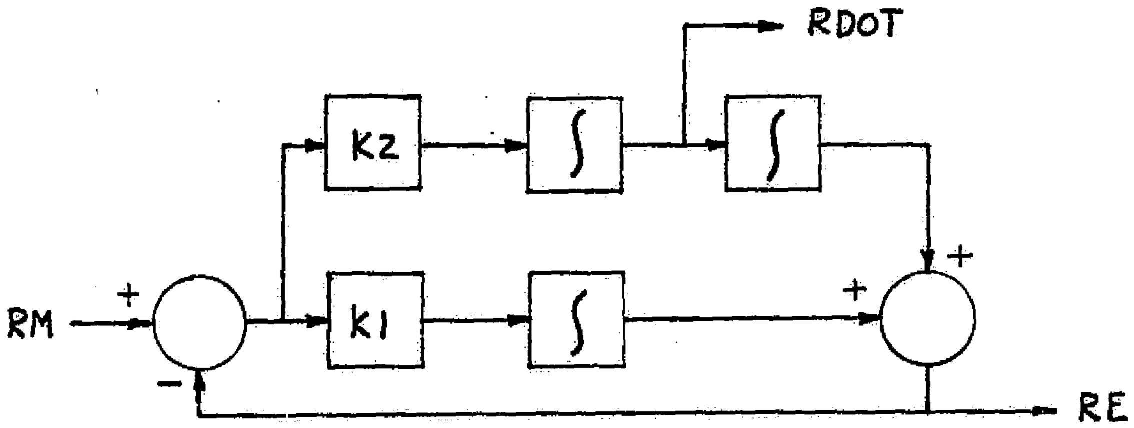


FIGURE 1 - Filter 1 (continuous system)

The discrete system is constructed by replacing the integrators in Figure 1 with discrete integrators using Euler's approximation. A delay must also be added to the feedback loop to make the system physically realizable. This method of mapping from the s-plane to the z-plane is

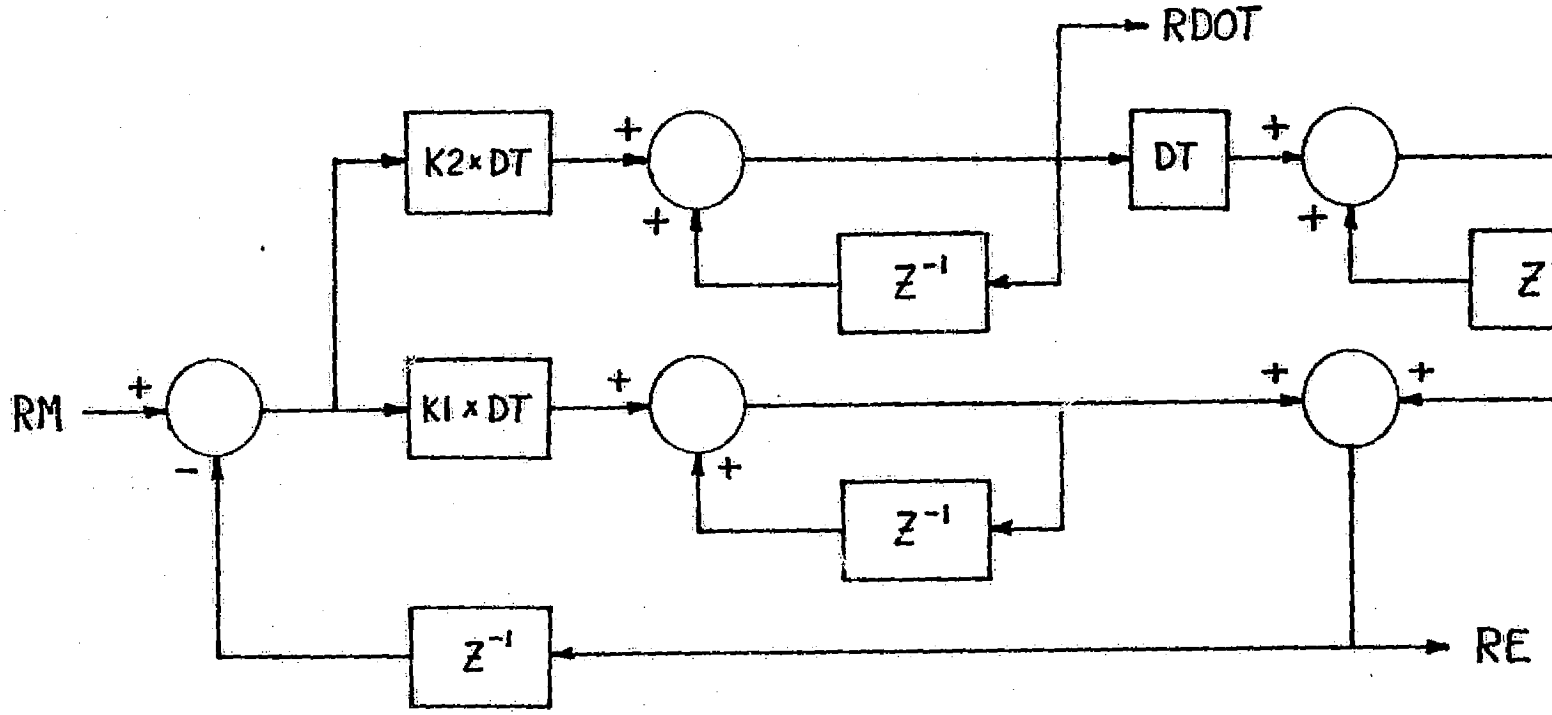


FIGURE 2 - Filter 1 (discrete system)

discussed in further detail in Appendix E. The resulting discrete system is presented in Figure 2. This system is characterized by the transfer functions:

$$H_R(z) = \frac{RE}{RM} = \frac{K1DT + K2DT^2 - z^{-1}(K1DT)}{1 + z^{-1}(-2 + K1DT + K2DT^2) + z^{-2}(1 - K1DT)} \qquad (3)$$

$$H_{RR}(z) = \frac{RDOT}{RM} = \frac{K2DT - z^{-1}(K2DT)}{1 + z^{-1}(-2 + K1DT + K2DT^2) + z^{-2}(1 - K1DT)} \qquad (4)$$

The classification of filters described by equations (1) and (2) is termed constant gains. This type of filter is simulated for five sets of parameter pairs, K1 and K2. In addition, if the parameter pairs are chosen such that

$$K1 = b\sqrt{2} \qquad (5)$$

and

$$K2 = b^2, \qquad (6)$$

where b is a frequency scaling parameter, the constant gains filter becomes a bandlimited differentiator.[1] Filter 1 is also simulated for five parameter sets chosen in accordance with equations (5) and (6).

B. Filter 2

Filter 2 is an alpha-beta tracking filter described by the difference equations:

$$RE(n) = RDI(n) + \alpha\,(RM(n) - RDI(n)) \tag{7}$$

$$RDOT(n) = RDOT(n-1) + \frac{\beta}{DT}(RM(n) - RDI(n)) \tag{8}$$

$$RDI(n+1) = RE(n) + DT(RDOT(n)) \tag{9}$$

A block diagram is presented in Figure 3.

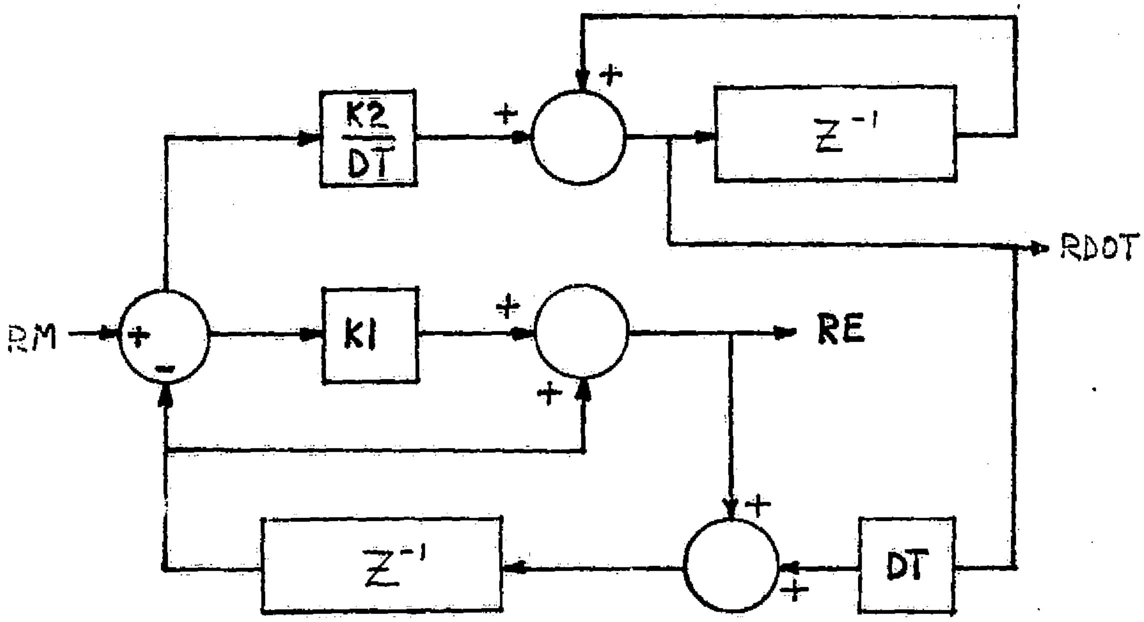


FIGURE 3 - Filter 2

At the n^{th} sample period three values are computed: the estimated range at that sample period, RE(n); the estimated range rate at that sample period, RDOT(n); and a predicted value of the range at the $(n + 1)^{th}$ sample period, RDI(n+1). The input value is RM(n), and DT is the sample interval. The response of this type filter is controlled by the parameters α and β. For this application, the relation

$$\beta = \frac{\alpha^2}{2 - \alpha} \tag{10}$$

is used to yield the maximum maneuver-following capabilities for a given level of noise rejection.[2] This results in the trade-off between noise rejection and maneuver-follwing capability being controlled by only one parameter, α.

The alpha-beta tracker remains a stable system for α and β bounded by[3]

$$\alpha > 0,\ \beta > 0 \text{ and } 2\alpha + \beta < 4. \tag{11}$$

For $\alpha = \beta = 1$ (a point on the curve denoted by (10) within the region specified by (11)), the system has a wide bandwidth and reacts quickly to transients. However, the transient-following capability is offset by poor noise rejection. The converse occurs for $\alpha \ll 1$, where the system is slow and has a comparatively low bandwidth. Noise rejection is much improved, but the system reacts more slowly to transients.

The transfer functions for the alpha-beta tracker are

$$H_R(z) = \frac{RE}{RM} = \frac{\alpha + (\beta-\alpha)z^{-1}}{1 + (-2 + \alpha + \beta)z^{-1} + (1 - \alpha)z^{-2}} \tag{12}$$

$$H_{RR}(z) = \frac{RDOT}{RM} = \frac{1}{DT}\ \frac{\beta - \beta z^{-1}}{1 + (-2 + \alpha + \beta)z^{-1} + (1 - \alpha)z^{-2}} \tag{13}$$

$$H_{R_p}(z) = \frac{RDI}{RM} = \frac{(\alpha + \beta)z^{-1} - \alpha z^{-2}}{1 + (-2 + \alpha + \beta)z^{-1} + (1 - \alpha)z^{-2}}\ , \tag{14}$$

where H_{R_p} is the transfer function for the predicted range, RDI. It is interesting to note that the transfer function H_{RR} for Filter 1 can be made identical to H_{RR} for the alpha - beta tracker if the parameter pair K1 and K2 are chosen such that

$$\alpha = K1 * DT \tag{15}$$

and

$$\beta = K2 * DT^2 \ . \tag{16}$$

The range transfer functions, H_R for Filter 1 and H_{R_p} for the alpha-beta tracker, are also very similar in that they differ only by a factor of z^{-1}. The main difference between the two filters is that the transfer function coefficients are dependent on sampling rate in Filter 1 and independent of sampling rate in Filter 2, the alpha-beta tracker. Simulation verifies that the two filters can be made to perform identically in the range rate mode and very closely in the range mode.

C. Filter 3

A functional block diagram of Filter 3 is presented in Figure 4. Eighteen registers containing the most recent and the previous seventeen range inputs are used in a cascaded simple average smoother to derive range rate. The sum of the six oldest range values is subtracted from the six most recent values. The result is a sum of six terms in which each term is the change in range that occurs over twelve sample periods. Division by six yields an average change in

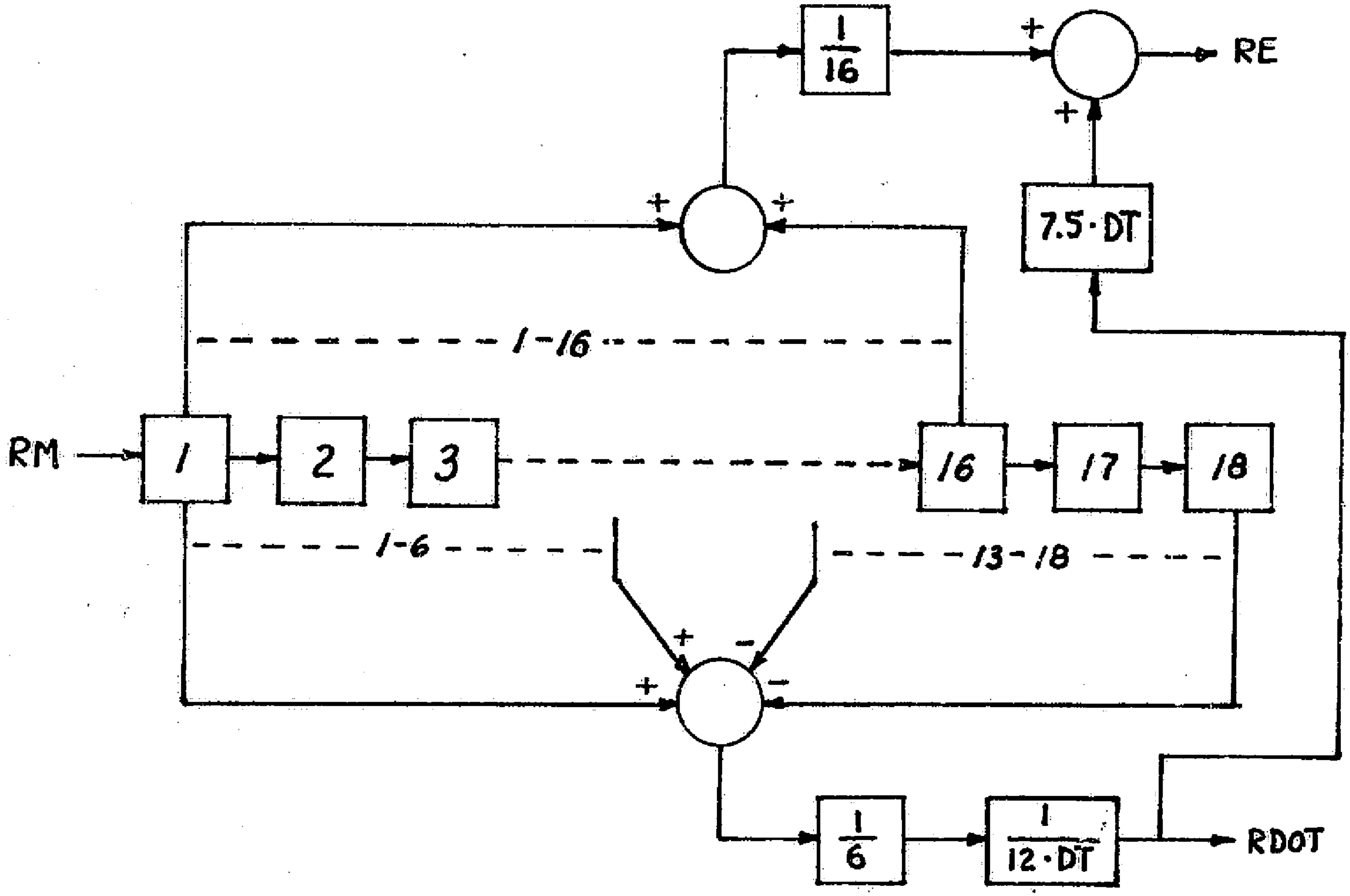


FIGURE 4 - Filter 3

range over twelve sample periods. Further division by 12 * DT then results in an estimated range rate value.

An N sample smoother is used to determine smoothed range. The sixteen most recent range inputs are averaged to yield a smoothed range delayed by 7.5 sampling periods from the current sampling period. The current range rate is used to determine a correction term that is added to the smoothed range to update it to the current sampling period.

D. Filter 4

Filter 4 is a digital tracking filter constructed by decreasing the number of storage registers and adding feedback to the design of Filter 3. A block diagram of Filter 4 is presented below.

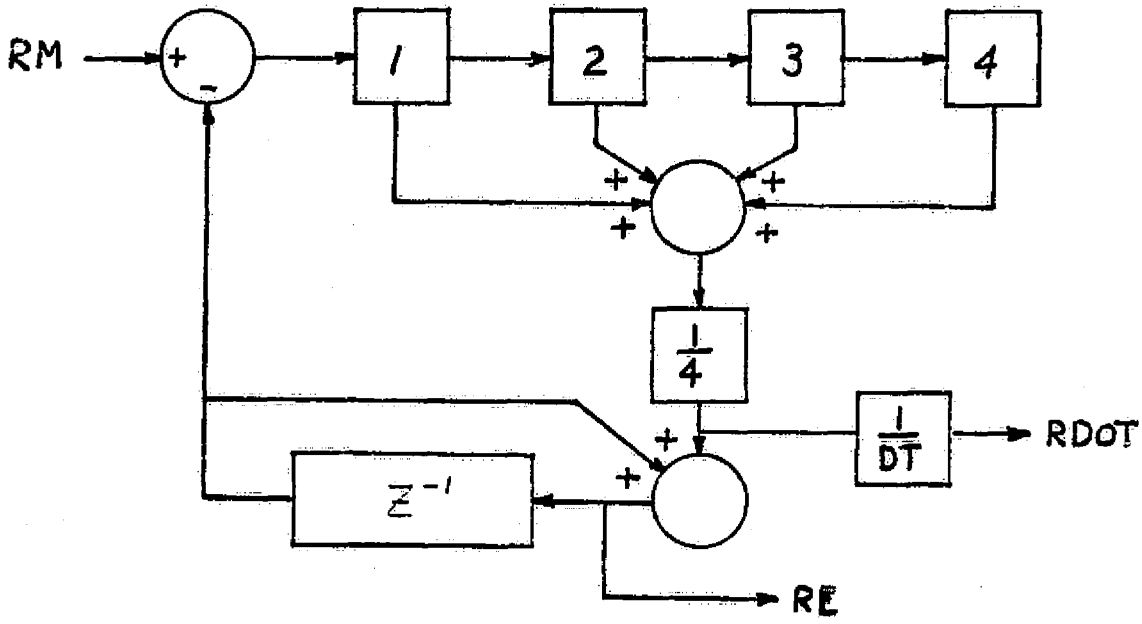


FIGURE 5 - Filter 4

In this design the values contained in the four storage registers now represent range error terms, rather than range terms, due to the addition of feedback. An average of these four registers is taken resulting in an average range error term. This value is added to the previous estimated range to yield the new estimated range. The estimated range rate value is determined by dividing the average range error term by the sampling period DT. The estimated range is then fed back to the sampled range input to produce a new range error term.

Four is the maximum number of storage registers (samples) that will result in a stable system.[4]

E. Filter 5

Filter 5 is a tracking filter similar to Filter 4 except for the addition of skip sampling. In this design, although the sixteen storage registers are still updated every sample instance, the range feedback term is updated only every sixteen sample periods. Estimated range and range rate are also available only at sixteen-sample-period intervals. A block diagram of Filter 5 is provided in Figure 6.

Every sixteenth sample, two range values are determined: the estimated range at that sample instant and the feedback range which lags the estimated range by 7.5 sample periods. The feedback range is subtracted from each of the next sixteen range inputs so that the value in the sixteenth storage register represents the change in range over 8.5 sample periods, and the value in the fifteenth register represents the change in range over 9.5 sample periods. This same pattern continues through the first storage register which contains the change in range over 23.5 sample periods. An average taken of the sixteen storage registers then yields a value that represents the smoothed change in range over sixteen sample periods. This value is added to

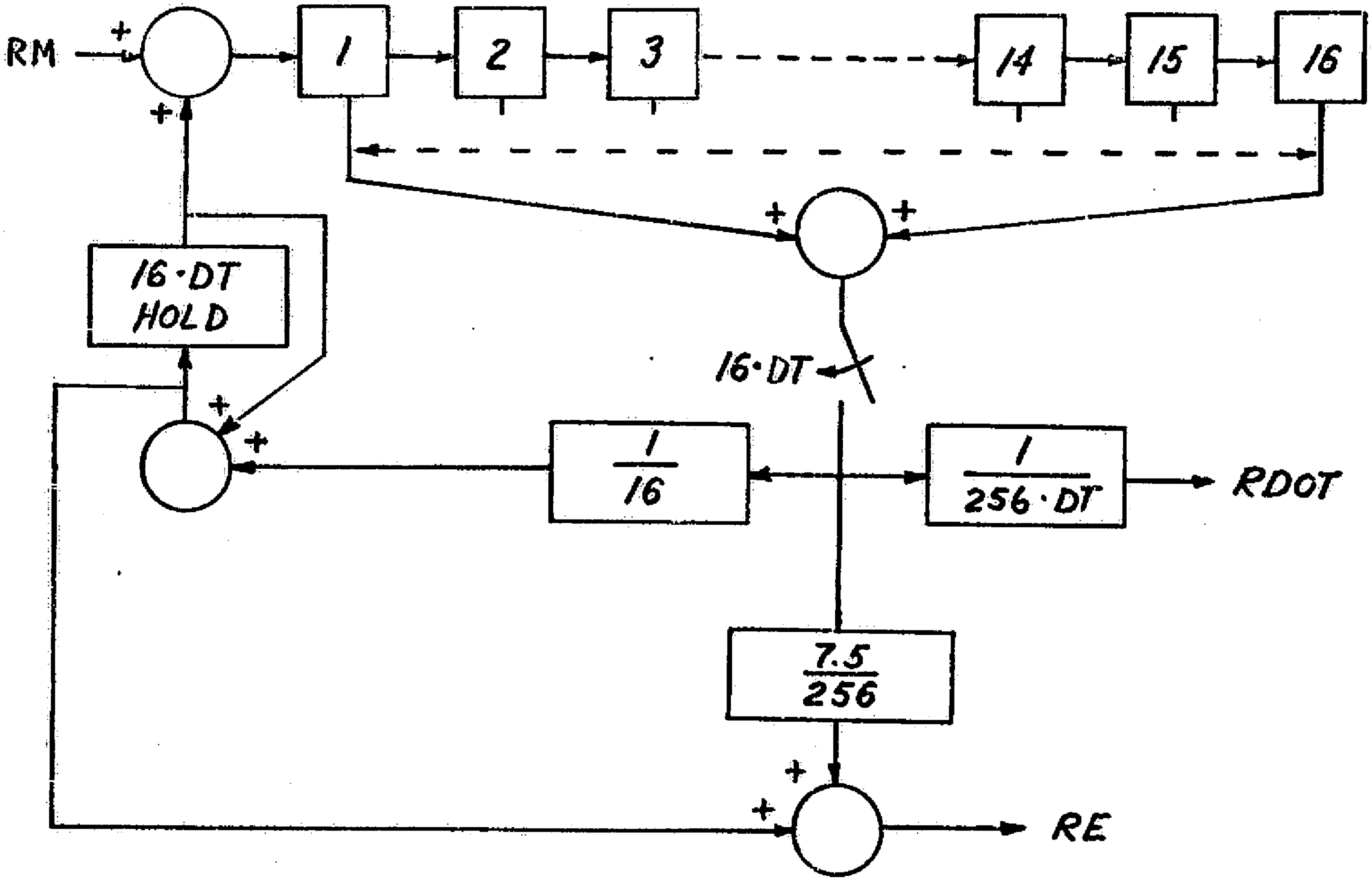


FIGURE 6 - Filter 5

the present feedback range to determine the feedback range to be used for the next set of sixteen range inputs. The smoothed change in range over sixteen sample periods is then multiplied by the ratio 7.5/16, and the result is added to the new feedback range to yield the estimated range for the present sample. The estimated range rate can be derived by dividing the smoothed change in range by sixteen to determine the change in range over one sample period. Division by the sample period then yields the estimated range rate.

III. IBM 370 COMPUTER SIMULATIONS

A. Description of Simulating Program

Program FLT is the FORTRAN program used in the IBM 370 simulations. In this program an initial range value and range rate value are entered to create a range signal of constant slope. This ramp simulates an object moving with constant velocity and is termed the true or actual range. A random number generator is used to create an array of normally distributed noise values of specified mean and standard deviation. Each filter is simulated for three range inputs. Simulation RUN 1 tests the filter response to the ramp, RUN 2 tests with the noise and RUN 3 uses a range input that is the summation of the ramp and the noise.

Filter calculations are performed by subroutine CALC. This subroutine also determines the input range value for a given sample period. That value is entered into the filter algorithm, and an estimated range and range rate value for that sample period are determined. The value IDI in the program determines how many times this process is repeated before program control returns to FLT. CALC returns to FLT the value at the most recent sampling period of the actual range, the range input, the estimated range, the actual range rate and the estimated range rate. These values along with the range error and range rate error, as determined from the differences of the estimated and actual range and range rate values, are output in tabulated form and saved in an array to be used in plotting. The value IDRI determines how many times subroutine CALC is called.

At the end of a simulation run, program FLT calculates statistics on the steady state values of various range and range rate signals. The subroutine BECORI is called from the International Mathematical and Statistical Library for this function. The mean and standard deviation are calculated for a set of sample values of the input range, estimated range and the estimated range rate. For all simulation runs at 2500 samples/second and 6.25 samples/second, the last 50 sample values of each of the three signals are saved in an array to be analyzed by BECORI. Since the last 50 samples are used, it is necessary that the simulation runs be of sufficient duration to allow initial transients to abate. This will insure that the samples represent steady state signals so that statistically accurate results can be obtained.

Program FLT contains two plotting routines for graphical representation of data. The first, PLOT B, implements the printer as a plotter. Although it provides limited resolution it is useful as a quick check of simulation results. The second routine, MCPLOT, formats data for a drum type plotter. After simulation RUN 3, four plots are generated for a particular filter - two range plots and two range rate plots . The first plot of each pair contains the graph of the actual signal and the resulting estimated signal over the full duration of that simulation run. However, in some cases the magnitude of the initial transient causes the scale of the plot to be too large to display any information on the steady state signal. For this reason, the second plot, an after-transient graph of the signal, is made. It displays the actual and estimated signals after a time delay to allow for decay of the transient. These four plots are generated for every filter being simulated. At the end of program FLT, after all filters have been simulated, four additional plots are generated. These contain the transient and after-transient graphs of the range error and range rate error signals. As an example, if two filters have been simulated, each of the four final plots will contain the graph of two signals -- one for each filter. This allows for a comparison of filter results.

As a clarification, only one type filter can be simulated during a given execution of program FLT, where type of filter refers to Filter 1, Filter 2, etc. References made in the above text to different filters being simulated during the same execution of program FLT mean different parameter pairs such as K1 and K2 used in the same type filter.

A listing of program FLT, subroutine CALC for each of the five filter types, and the plotting routines, PLOT B and MCPLOT, are given in Appendix A.

B. Test Conditions

As previously noted, three simulation runs are made to evaluate each filter. For the first run, the input signal is a ramp function representing actual range and is described by the equation:

$$r(t) = 60800 - 28t. \tag{17}$$

This is a ramp of negative slope corresponding to an initial range of 18.532 Km (60800 ft.) and a range rate of -8.5344 m/sec.(-28 ft./sec.). The purpose of this run is to evaluate the ability of the filter to accurately track an object moving at constant velocity. This input signal has been used in previous investigations of range rate filters.

The second simulation run determines how well the filter rejects random noise. The input signal is Gaussian noise with a mean (μ) of zero and a standard deviation (σ) of 30.48 m (100 ft.)

The purpose of the third run is to evaluate the response of the filter to noisy range data. The input signal is a summation of the inputs for the previous two runs. This input can be termed a noisy ramp. This run shows what effect the addition of noise has on the ability of the filter to track the actual range value.

In the first set of tests, all filters are run at a sampling rate of 2500 samples/second for a period of 75 seconds. Results are tabulated at one second intervals, and the steady state statistics, mean and standard deviation, are taken on the last 50 samples.

The second set of simulations are made at 6.25 samples/second for a duration of 192 seconds. Results are tabulated every 16 sample periods or 2.56 seconds. Steady state statistics for these simulations are taken on the last 50 samples.

C. Test Results

Data for each filter is divided into two sections: that obtained at a 2500 samples/second sampling rate and that obtained at

6.25 samples/second. Data for each filter is provided in tables and in many cases also presented in graphical form to aid in visualizing actual range and range rate signals. A summary of the filter's performance is given at the beginning of the data for that filter.

Four tables are presented for each filter. The first table gives the input and output range standard deviations for each of the three simulation runs. The second table gives the output range rate standard deviations for each of the three simulation runs. These values give a measure of a signal's variance from its mean. In the case of simulation RUN 1, where the range input is the ramp representing actual range, the desired range output signal is an identical ramp. Hence, the standard deviation of the input and output range signals should ideally be equal. Since the slope of the ramp is constant, it is expected that the estimated range rate signal produced by the filter should also be constant and hence its standard deviation will approach zero. During simulation RUN 2, the input range signal is Gaussian noise of zero mean and known standard deviation. If the noise is indeed attenuated by the filter, then the estimated range output will show a reduction in standard deviation from that of the input range signal. Since the input represents a constant range value (namely zero range) with noise added, the optimum estimated range rate signal returned by the filter would again have a standard deviation approaching zero. The range input provided to the filter in simulation RUN 3 is that of the Gaussian noise superimposed on the ramp. If both the ramp and the noise are independent, random signals and the filter is a linear system, then

$$\sigma_R^2 + \sigma_N^2 = \sigma_{R+N}^2, \tag{18}$$

where σ_R^2 is the variance of the estimated range output for the ramp input, σ_N^2 is the variance for the estimated range output for the noise input and σ_{R+N}^2 is the variance for the estimated range output for the ramp plus noise or noisy ramp input. In this case σ_R^2, σ_N^2 and σ_{R+N}^2 would represent the square of the estimated range standard deviations for RUN 1, RUN 2 and RUN 3, respectively. However, although the ramp and noise are independent, the ramp is not a random signal so the above relation does not hold true. For this reason, RUN 3 is necessary to determine the results for a noisy ramp range input.

The third table contains the maximum steady state range and range rate errors for the three simulation runs. This information is presented to give another measure of the range over which an estimated range or range rate value will deviate from the actual value.

The fourth table lists the range variance reduction ratio, KR, and the range rate variance reduction ration, KRR. These ratios are determined from the relations:

$$KR = \frac{\text{variance of range output}}{\text{variance of range input}} \tag{19}$$

and

$$KRR = \frac{\text{variance of range rate output}}{\text{variance of range input}} . \tag{20}$$

The variance terms are the square of the standard deviations presented in the first and second tables under RUN 2. This is the simulation run conducted with Gaussian noise as the range input. Whereas the standard deviations provide information on specific signals, the reduction ratios offer a standardized method for comparison of filter results.

The fourth table also lists convergence time τ. This was arbitrarily defined as the time required for the estimated range to reach a steady state condition such that the magnitude of the range error does not exceed 3.048 m (10 ft.). The data used to determine τ is taken from simulation RUN 1, where the range input is the ramp.

1. Filter 1

Simulation data at 2500 samples/second for Filter 1 is presented in Tables I-IV for the constant gains filter and in Tables V-VIII for the bandlimited differentiator. Data at 6.25 samples/second is presented in Tables IX-XII for the constant gains filter and in Tables XIII-XVI for the bandlimited differentiator. A graphical display of the data at 2500 samples/second is shown for two sets of parameter pairs (K1, K2) for the constant gains filter in Figures 7-12 and for the bandlimited differentiator in Figures 13-18. Data at 6.25 samples/second is shown for the constant gains filter in Figures 19-24 and for the bandlimited differentiator in Figures 25-30.

The data indicates that Filter 1 has higher noise rejection at the higher sampling rate. Since this filter is a digital approximation to a continuous system, this is expected.

The digital system more closely approximates a continuous system as the sampling rate increases.

For the bandlimited differentiator (BLD) the effect of b, the frequency scaling parameter, can be noted by observing the variance reduction ratios. In the bandlimited differentiator, the cutoff frequency is determined by the frequency scaling parameter. As the scaling parameter is reduced, the bandwidth of the system decreases. Hence, more lower frequency components of the noise are attenuated and the variance reduction ratios decrease. This, however, also reduces the system's responsiveness to higher frequency changes in range signals which results in a reduction in maneuver-following capabilities. This is shown by the increase in convergence time as the frequency scaling parameter is reduced.

A comparison of the variance reduction ratios shows a slight advantage for the bandlimited differentiator over the constant gains filter. While the constant gains filter produces good range and range rate data, there appears to be a trade off between the two. With the bandlimited differentiator, changing the frequency scaling parameter to improve range data also has the effect of improving range rate performance (at the expense of convergence time).

There are a variety of methods to derive a discretized approximation to a continuous system. The method used in Filter 1 produces a system that is a predictor, i.e., the estimated range returned at the n^{th} sampling instant is a predicted value of the range at the $(n + 1)^{th}$ sampling instant. This effect can be observed in the maximum steady state range error for simulation

TABLE I

FILTER 1 RANGE STANDARD DEVIATIONS(FT.) AT 2500 SAMPLES/SEC.

	RUN 1 input = ramp		RUN 2 input = noise		RUN 3 input = ramp + noise	
FILTER 1 CONSTANT GAINS	INPUT RANGE STND. DEV.	OUTPUT RANGE STND. DEV.	INPUT RANGE STND. DEV.	OUTPUT RANGE STND. DEV.	INPUT RANGE STND. DEV.	OUTPUT RANGE STND. DEV.
K1 = 0.7071 K2 = 0.45	0.1634	0.1634	110.7364	0.8773×10^{-1}	110.7339	0.2463
K1 = 0.75 K2 = 0.125	0.1634	0.1634	110.7364	0.9391×10^{-1}	110.7339	0.2523
K1 = 0.7 K2 = 0.3769	0.1634	0.1634	110.7364	0.8717×10^{-1}	110.7339	0.2459
K1 = 0.49 K2 = 0.98995	0.1634	0.1632	110.7364	0.5529×10^{-1}	110.7339	0.2142
K1 = 0.75 K2 = 0.45	0.1634	0.1634	110.7364	0.9325×10^{-1}	110.7339	0.2511

TABLE II

FILTER 1 RANGE RATE STANDARD DEVIATIONS(FT./SEC.) AT 2500 SAMPLES/SEC.

FILTER 1 CONSTANT GAINS	RUN 1 input = range OUTPUT RANGE RATE STND. DEV.	RUN 2 input = noise OUTPUT RANGE RATE STND. DEV.	RUN 3 input = ramp + noise OUTPUT RANGE RATE STND. DEV.
K1 = 0.7071 K2 = 0.45	0.0	0.5652×10^{-1}	0.5652×10^{-1}
K1 = 0.75 K2 = 0.125	0.0	0.1575×10^{-1}	0.1575×10^{-1}
K1 = 0.7 K2 = 0.3769	0.0	0.4740×10^{-1}	0.4740×10^{-1}
K1 = 0.49 K2 = 0.98995	0.0	0.1238	0.1238
K1 = 0.75 K2 = 0.45	0.0	0.5662×10^{-1}	0.5661×10^{-1}

TABLE III

FILTER 1 MAXIMUM RANGE(FT.) AND RANGE RATE(FT./SEC.) ERRORS AT 2500 SAMPLES/SEC.

	RUN 1 input = ramp		RUN 2 input = noise		RUN 3 input = ramp + noise	
FILTER 1 CONSTANT GAINS	MAX RANGE ERROR	MAX RANGE RATE ERROR	MAX RANGE ERROR	MAX RANGE RATE ERROR	MAX RANGE ERROR	MAX RANGE RATE ERROR
K1 = 0.7071 K2 = 0.45	0.112×10^{-1}	0.140×10^{-6}	0.278	0.323	0.290	0.323
K1 = 0.75 K2 = 0.125	0.108×10^{-1}	0.221×10^{-3}	0.223	0.138	0.234	0.139
K1 = 0.7 K2 = 0.3769	0.112×10^{-1}	0.225×10^{-7}	0.247	0.264	0.258	0.264
K1 = 0.49 K2 = 0.98995	0.106×10^{-1}	0.464×10^{-4}	0.322	1.395	0.332	1.395
K1 = 0.75 K2 = 0.45	0.112×10^{-1}	0.241×10^{-7}	0.250	0.329	0.261	0.329

TABLE IV

FILTER 1 RANGE AND RANGE RATE VARIANCE REDUCTION RATIOS AT 2500 SAMPLES/SEC.

	RUN 2 input = noise		
FILTER 1 CONSTANT GAINS	KR RANGE VARIANCE REDUCTION RATIO	KRR RANGE RATE VARIANCE REDUCTION RATIO	τ CONVERGENCE TIME (SEC.)
K1 = 0.7071 K2 = 0.45	6.276×10^{-7}	2.605×10^{-7}	23
K1 = 0.75 K2 = 0.125	7.192×10^{-7}	2.023×10^{-8}	35
K1 = 0.7 K2 = 0.3769	6.197×10^{-7}	1.832×10^{-7}	25
K1 = 0.49 K2 = 0.98995	2.493×10^{-7}	1.250×10^{-6}	36
K1 = 0.75 K2 = 0.45	7.091×10^{-7}	2.614×10^{-7}	23

TABLE V

FILTER 1 RANGE STANDARD DEVIATIONS(FT.) AT 2500 SAMPLES/SEC.

	RUN 1 input = ramp		RUN 2 input = noise		RUN 3 input = ramp + noise	
FILTER 1 BLD	INPUT RANGE STND. DEV.	OUTPUT RANGE STND. DEV.	INPUT RANGE STND. DEV.	OUTPUT RANGE STND. DEV.	INPUT RANGE STND. DEV.	OUTPUT RANGE STND. DEV.
K1 = 0.7778 K2 = 0.3025 b = 0.55	0.1634	0.1634	110.7364	0.9729×10^{-1}	110.7339	0.2251
K1 = 0.7071 K2 = 0.25 b = 0.50	0.1634	0.1634	110.7364	0.8841×10^{-1}	110.7339	0.2468
K1 = 0.6364 K2 = 0.2025 b = 0.45	0.1634	0.1634	110.7364	0.7951×10^{-1}	110.7339	0.2381
K1 = 0.5657 K2 = 0.160 b = 0.40	0.1634	0.1632	110.7364	0.7056×10^{-1}	110.7339	0.2296
K1 = 0.4950 K2 = 0.1225 b = 0.35	0.1634	0.1633	110.7364	0.6157×10^{-1}	110.7339	0.2211

TABLE VI

FILTER 1 RANGE RATE STANDARD DEVIATIONS(FT./SEC.) AT 2500 SAMPLES/SEC.

FILTER 1 BLD	RUN 1 input = ramp OUTPUT RANGE RATE STND. DEV.	RUN 2 input = noise OUTPUT RANGE RATE STND. DEV.	RUN 3 input = ramp + noise OUTPUT RANGE RATE STND. DEV.
K1 = 0.7778 K2 = 0.3025 b = 0.55	0.0	0.3818×10^{-1}	0.3818×10^{-1}
K1 = 0.7071 K2 = 0.25 b = 0.50	0.0	0.3155×10^{-1}	0.3155×10^{-1}
K1 = 0.6364 K2 = 0.2025 b = 0.45	0.0	0.2556×10^{-1}	0.2556×10^{-1}
K1 = 0.5657 K2 = 0.160 b = 0.40	0.0	0.2019×10^{-1}	0.2019×10^{-1}
K1 = 0.4950 K2 = 0.1225 b = 0.35	0.0	0.1544×10^{-1}	0.1544×10^{-1}

TABLE VII

FILTER 1 MAXIMUM RANGE(FT.) AND RANGE RATE(FT./SEC.) ERRORS AT 2500 SAMPLES/SEC.

	RUN 1 input = ramp		RUN 2 input = noise		RUN 3 input = ramp + noise	
FILTER 1 BLD	MAX RANGE ERROR	MAX RANGE RATE ERROR	MAX RANGE ERROR	MAX RANGE RATE ERROR	MAX RANGE ERROR	MAX RANGE RATE ERROR
K1 = 0.7778 K2 = 0.3025 b = 0.55	0.112	0.901×10^{-8}	0.208	0.246	0.197	0.246
K1 = 0.7071 K2 = 0.25 b = 0.50	0.112	0.128×10^{-6}	0.187	0.223	0.178	0.223
K1 = 0.6364 K2 = 0.2025 b = 0.45	0.112×10^{-1}	0.161×10^{-5}	0.172	0.208	0.161	0.208
K1 = 0.5657 K2 = 0.160 b = 0.40	0.111×10^{-1}	0.149×10^{-4}	0.152	0.199	0.142	0.199
K1 = 0.4950 K2 = 0.1225 b = 0.35	0.119×10^{-1}	0.757×10^{-4}	0.143	0.188	0.155	0.188

TABLE VIII

FILTER 1 RANGE AND RANGE RATE VARIANCE REDUCTION RATIOS AT 2500 SAMPLES/SEC.

	RUN 2 input = noise		
FILTER 1 BLD	KR RANGE VARIANCE REDUCTION RATIO	KRR RANGE RATE VARIANCE REDUCTION RATIO	τ CONVERGENCE TIME (SEC.)
K1 = 0.7778 K2 = 0.3025 b = 0.55	7.719×10^{-7}	1.189×10^{-7}	24
K1 = 0.7071 K2 = 0.25 b = 0.50	6.374×10^{-7}	8.117×10^{-8}	26
K1 = 0.6364 K2 = 0.2025 b = 0.45	5.155×10^{-7}	5.328×10^{-8}	29
K1 = 0.5657 K2 = 0.160 b = 0.40	4.060×10^{-7}	3.324×10^{-8}	32
K1 = 0.4950 K2 = 0.1225 b = 0.35	3.091×10^{-7}	1.944×10^{-8}	37

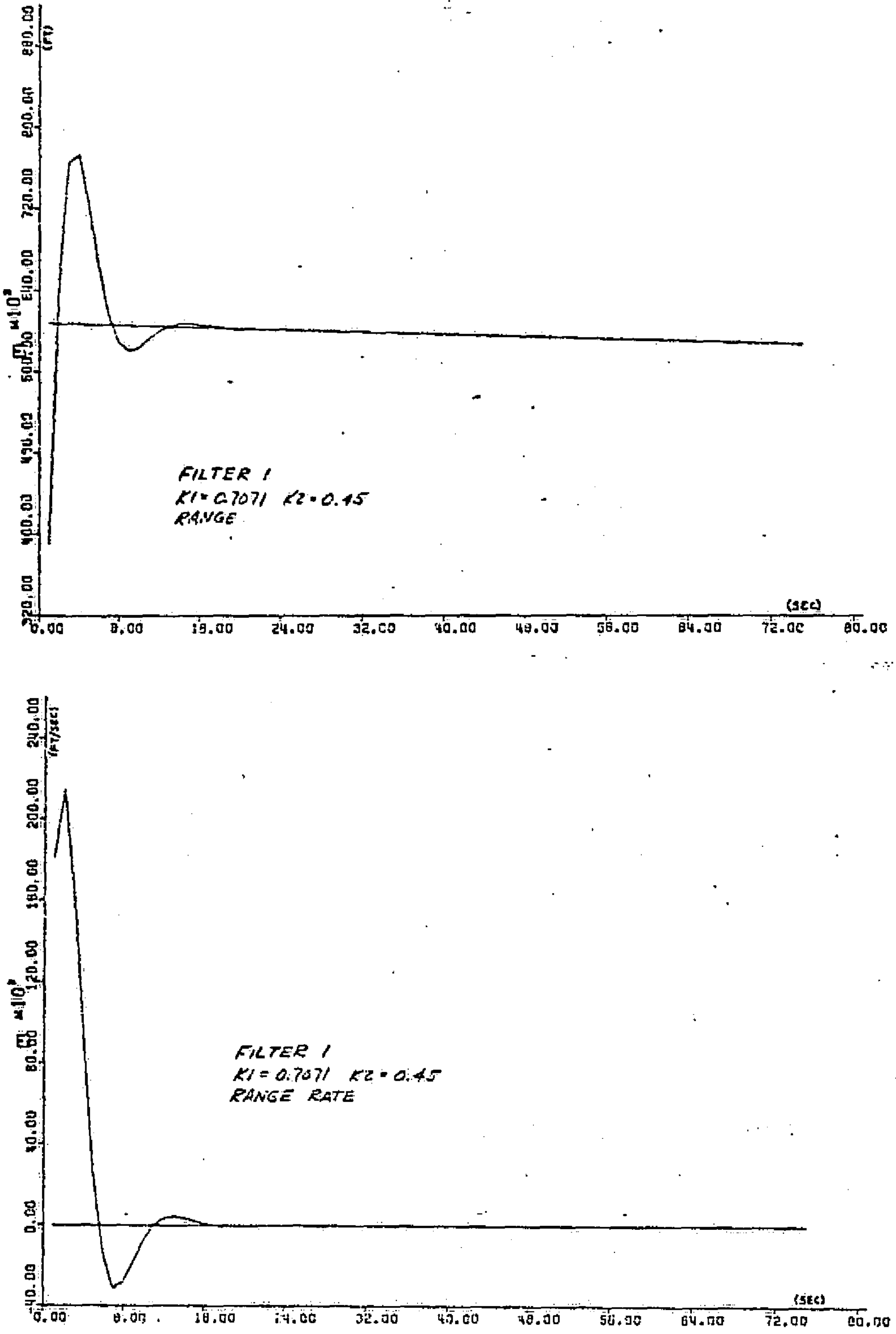


FIGURE 7 - Filter 1 (Constant Gains) at 2500 samples/sec.

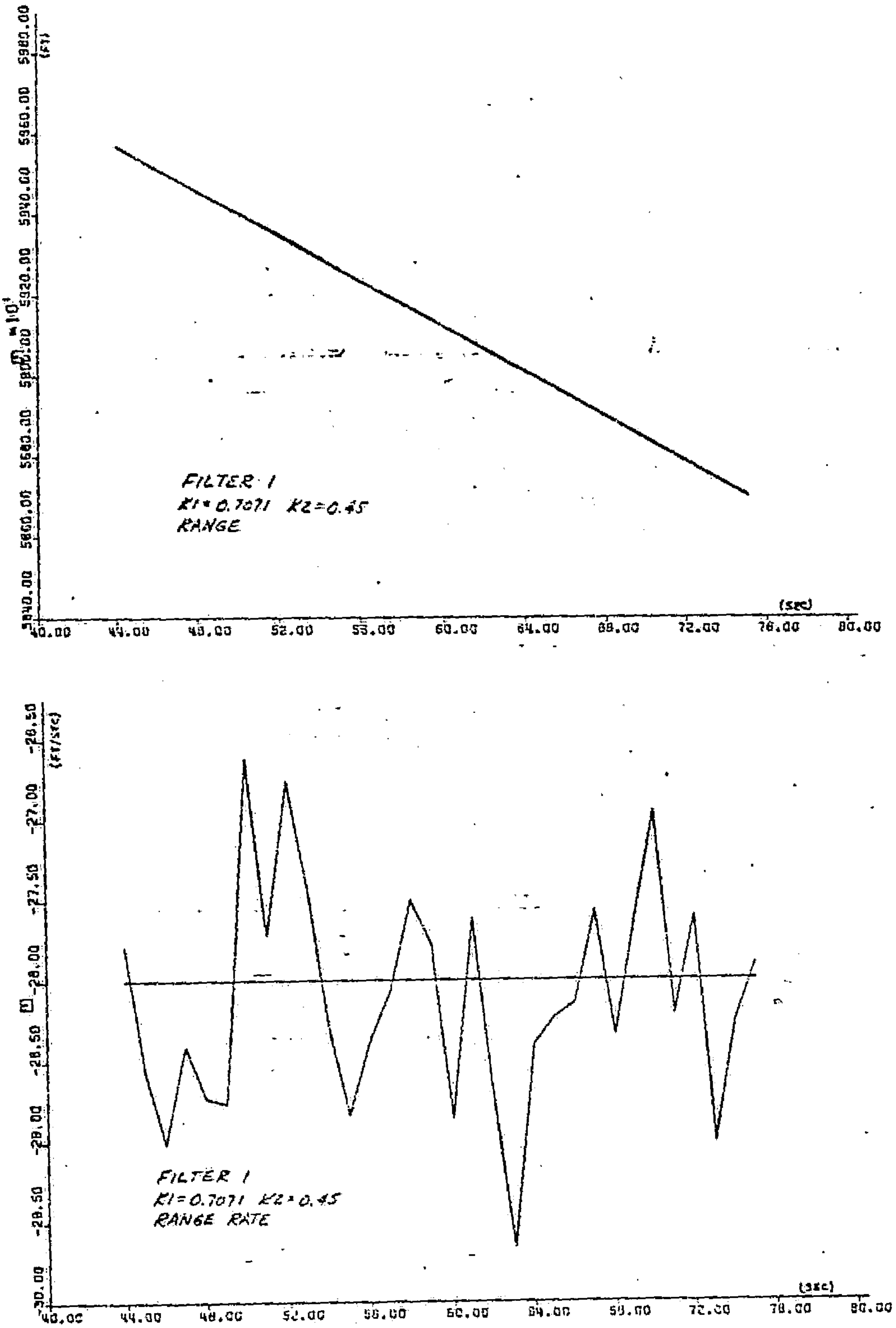


FIGURE 8 - Filter 1 (Constant Gains) at 2500 samples/sec.

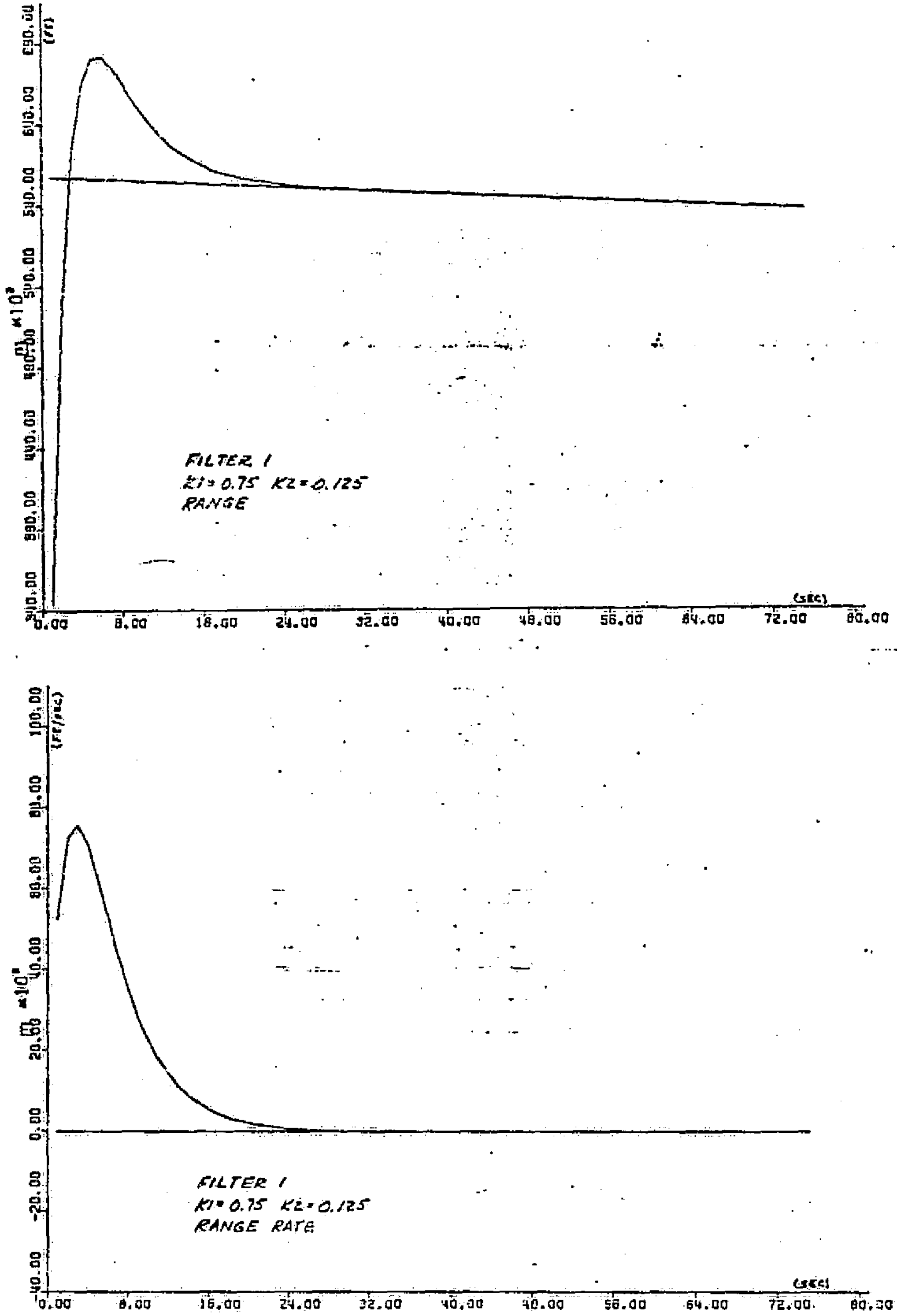


FIGURE 9 - Filter 1 (Constant Gains) at 2500 samples/sec.

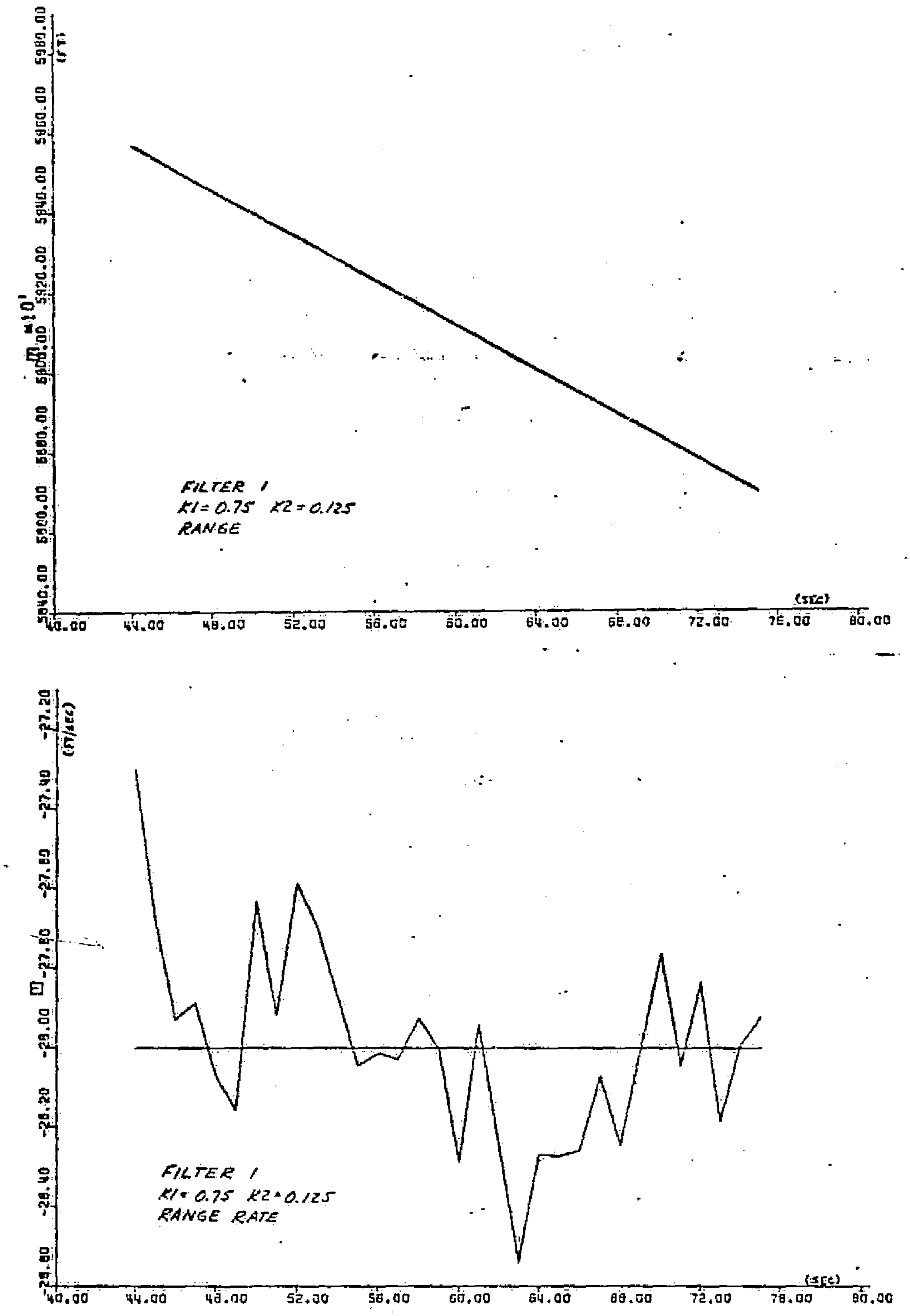


FIGURE 10 - Filter 1 (Constant Gains) at 2500 samples/sec.

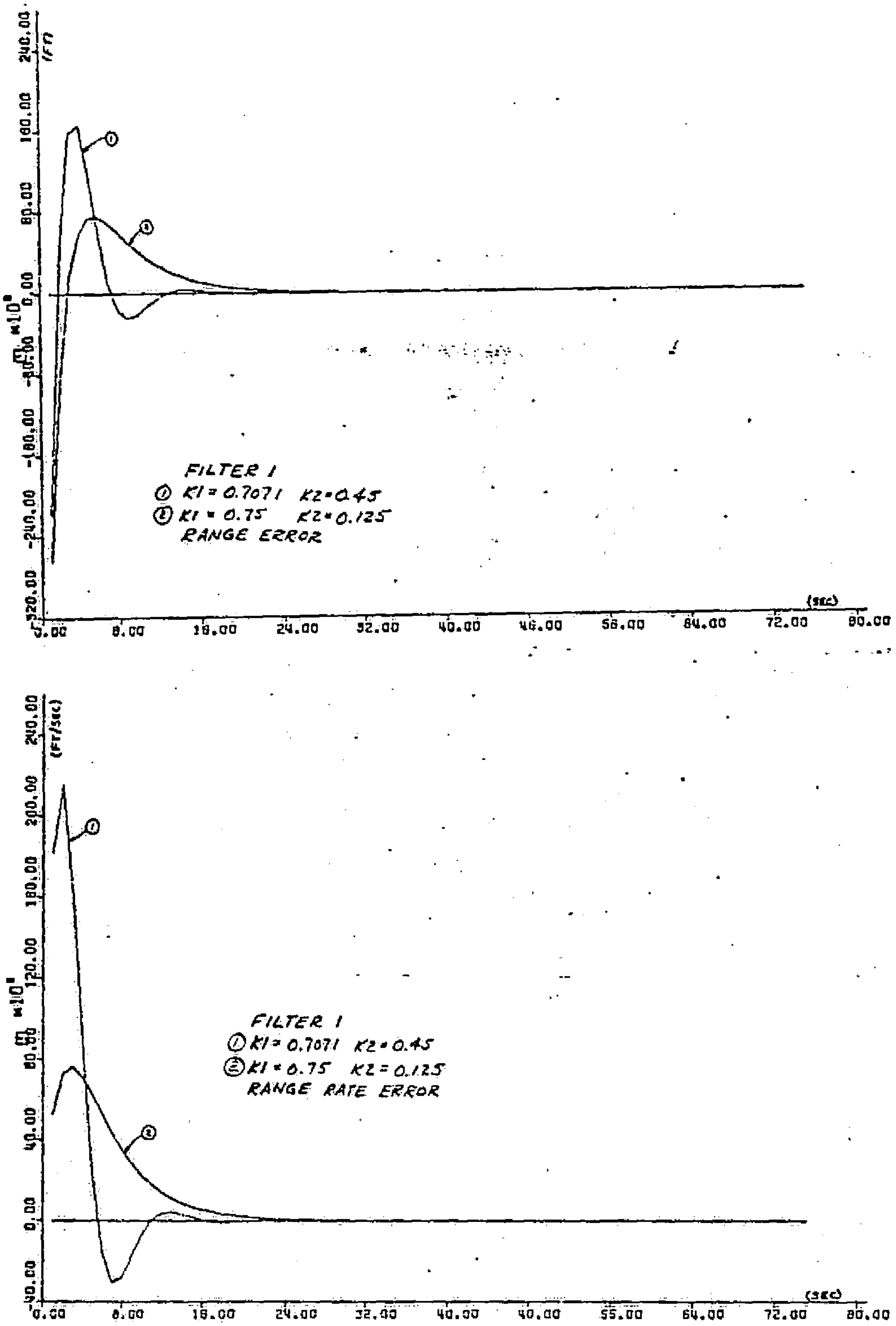


FIGURE 11 - Filter 1 (Constant Gains) at 2500 samples/sec.

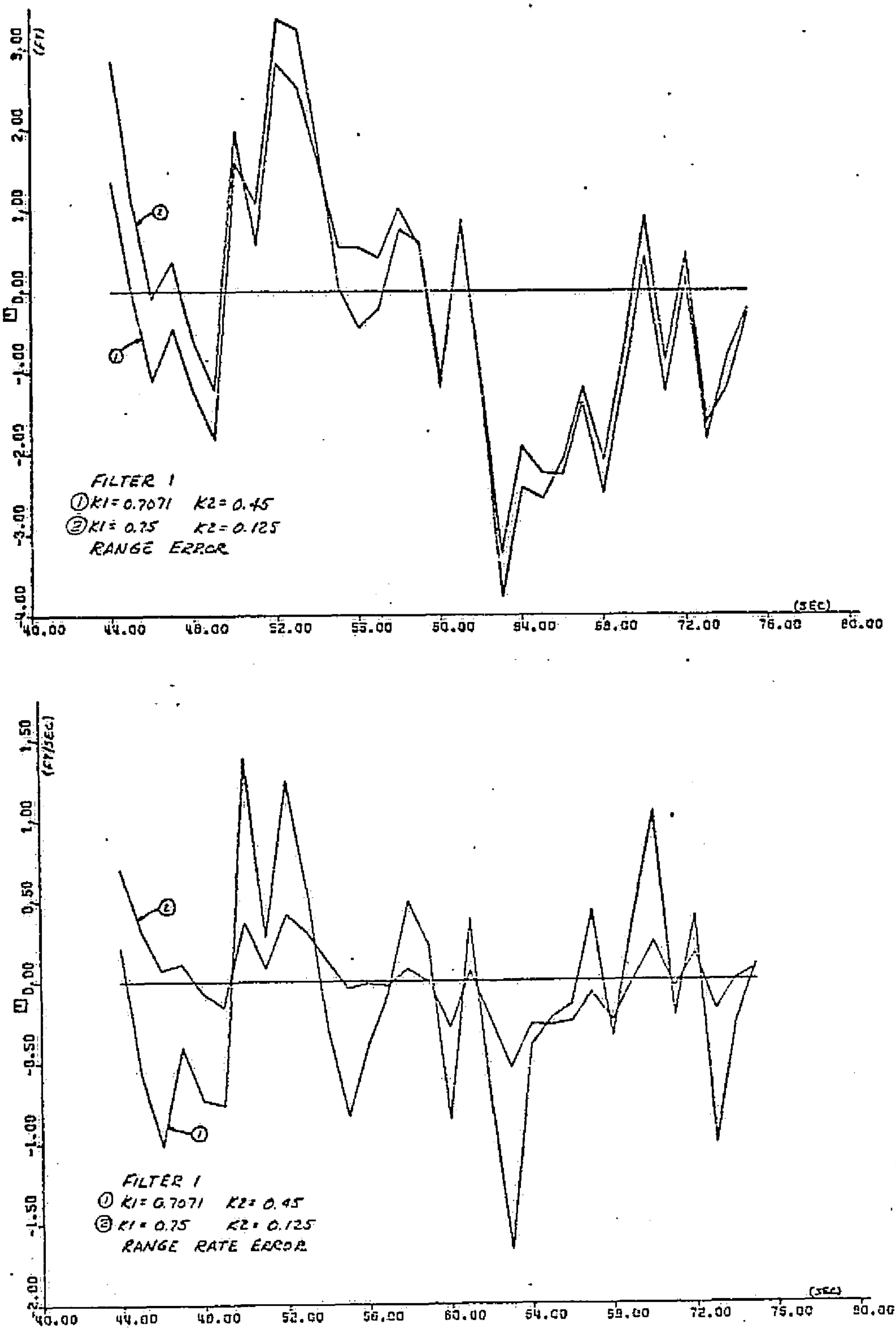


FIGURE 12 - Filter 1 (Constant Gains) at 2500 samples/sec.

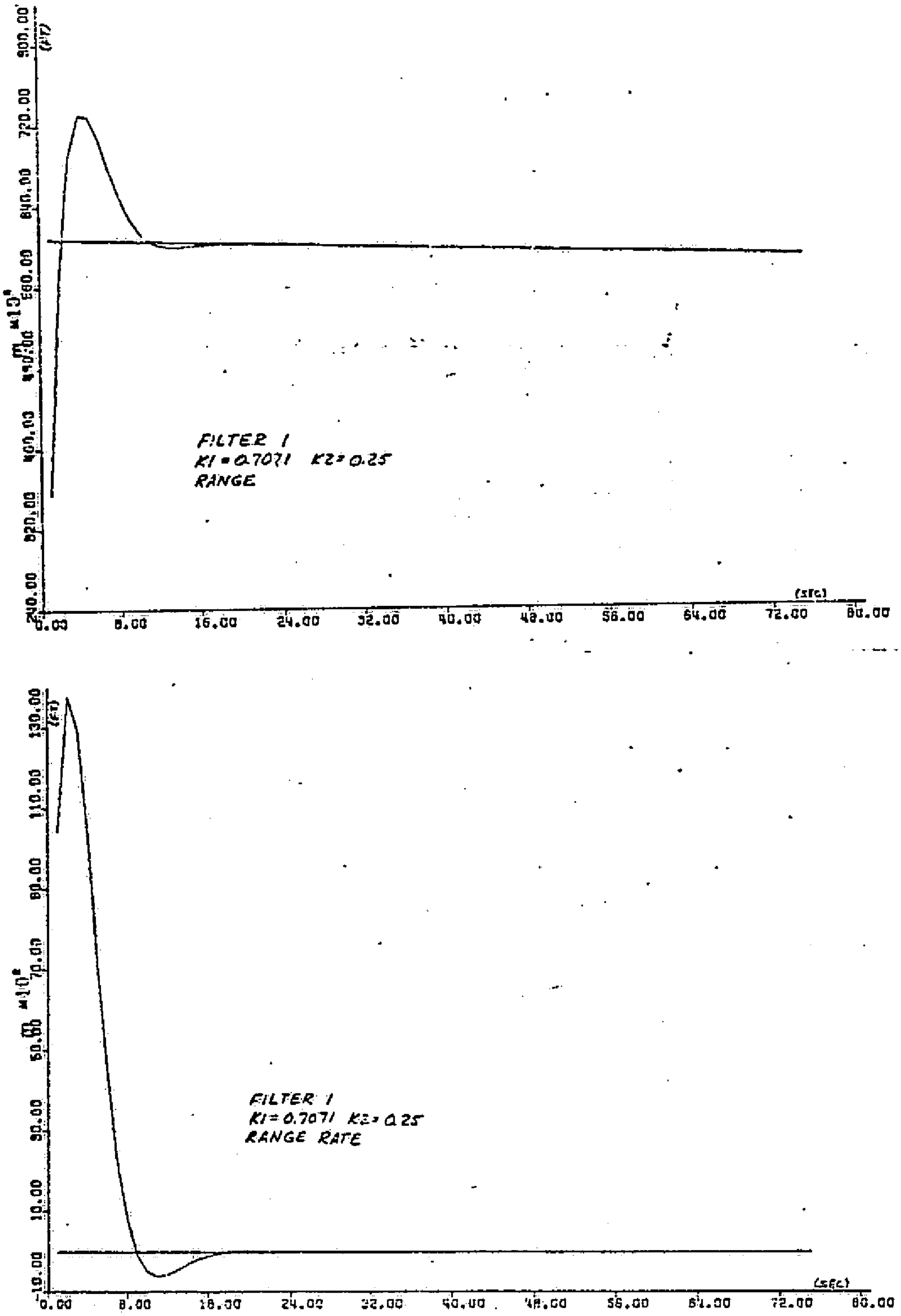


FIGURE 13 - Filter 1 (BLD) at 2500 samples/sec.

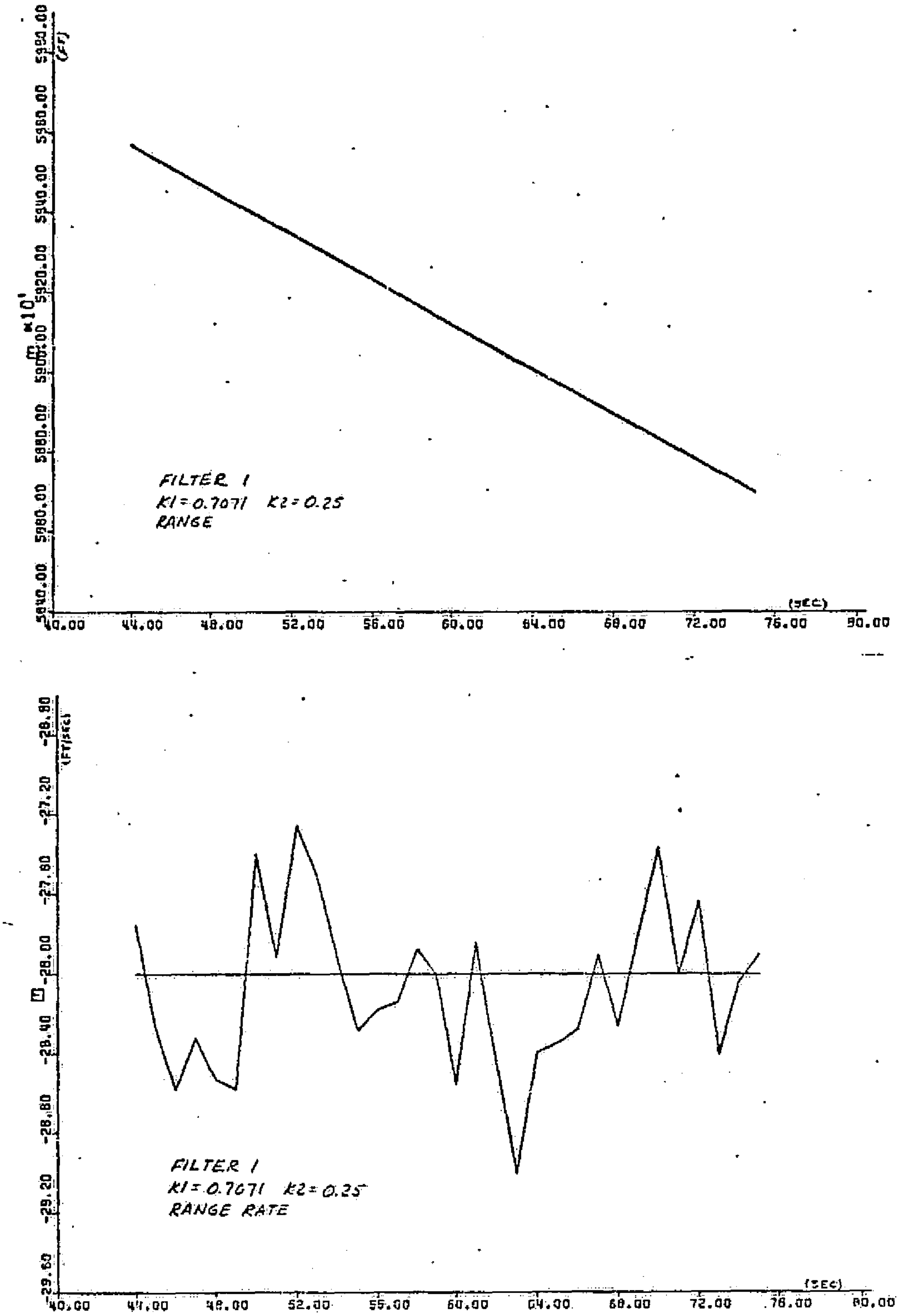


FIGURE 14 - Filter 1 (BLD) at 2500 samples/sec.

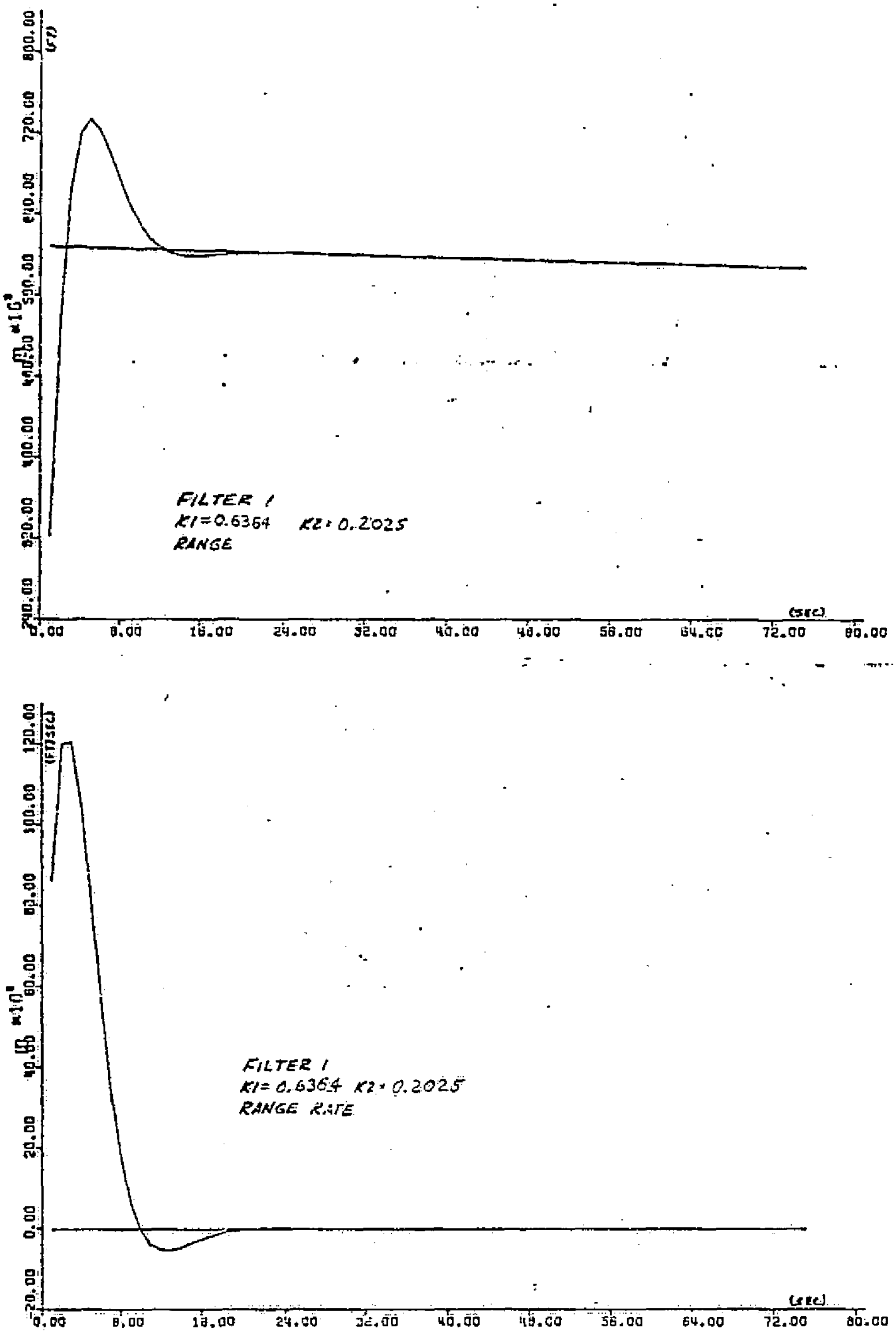


FIGURE 15 - Filter 1 (BLD) at 2500 samples/sec.

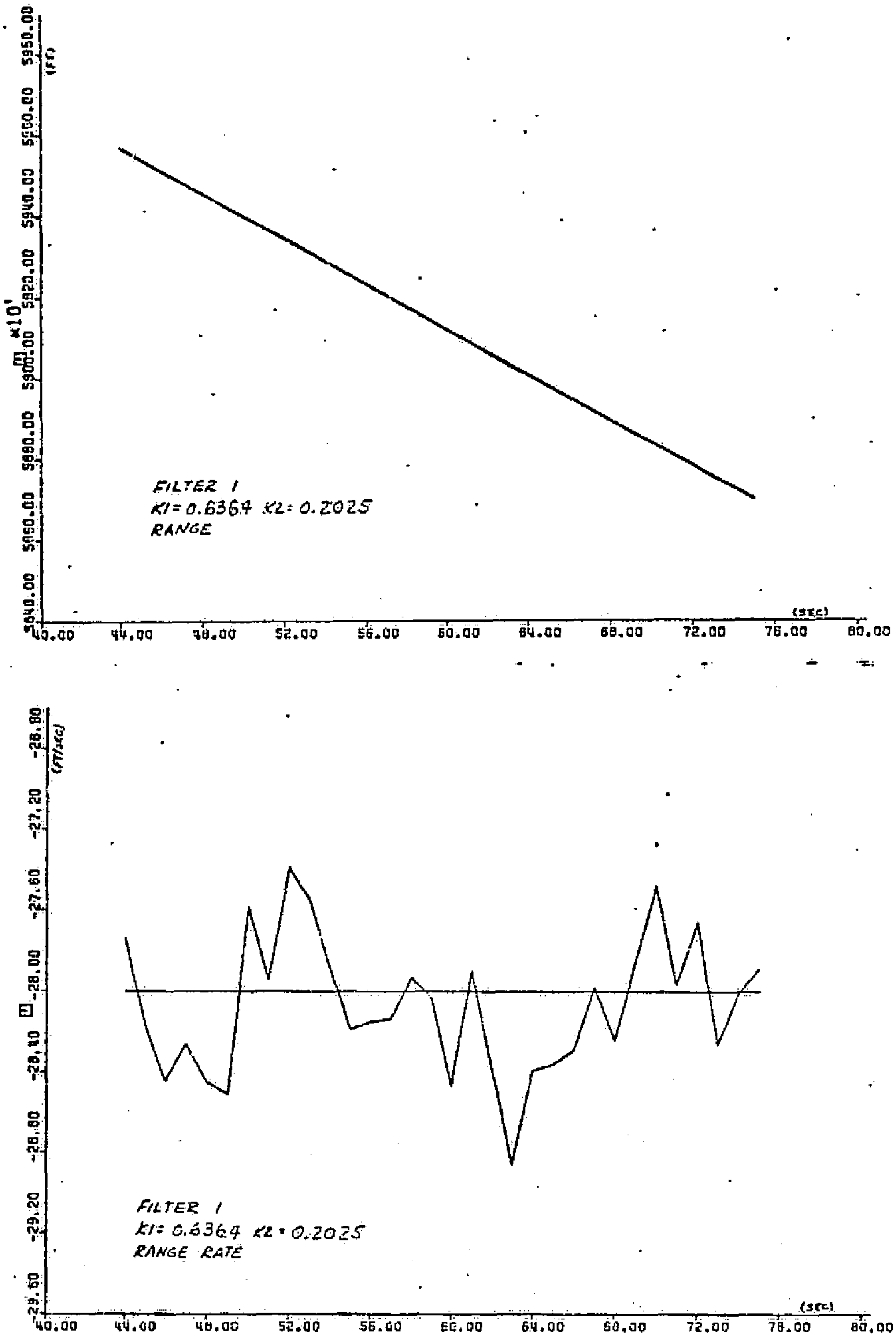


FIGURE 16 - Filter 1 (BLD) at 2500 samples/sec.

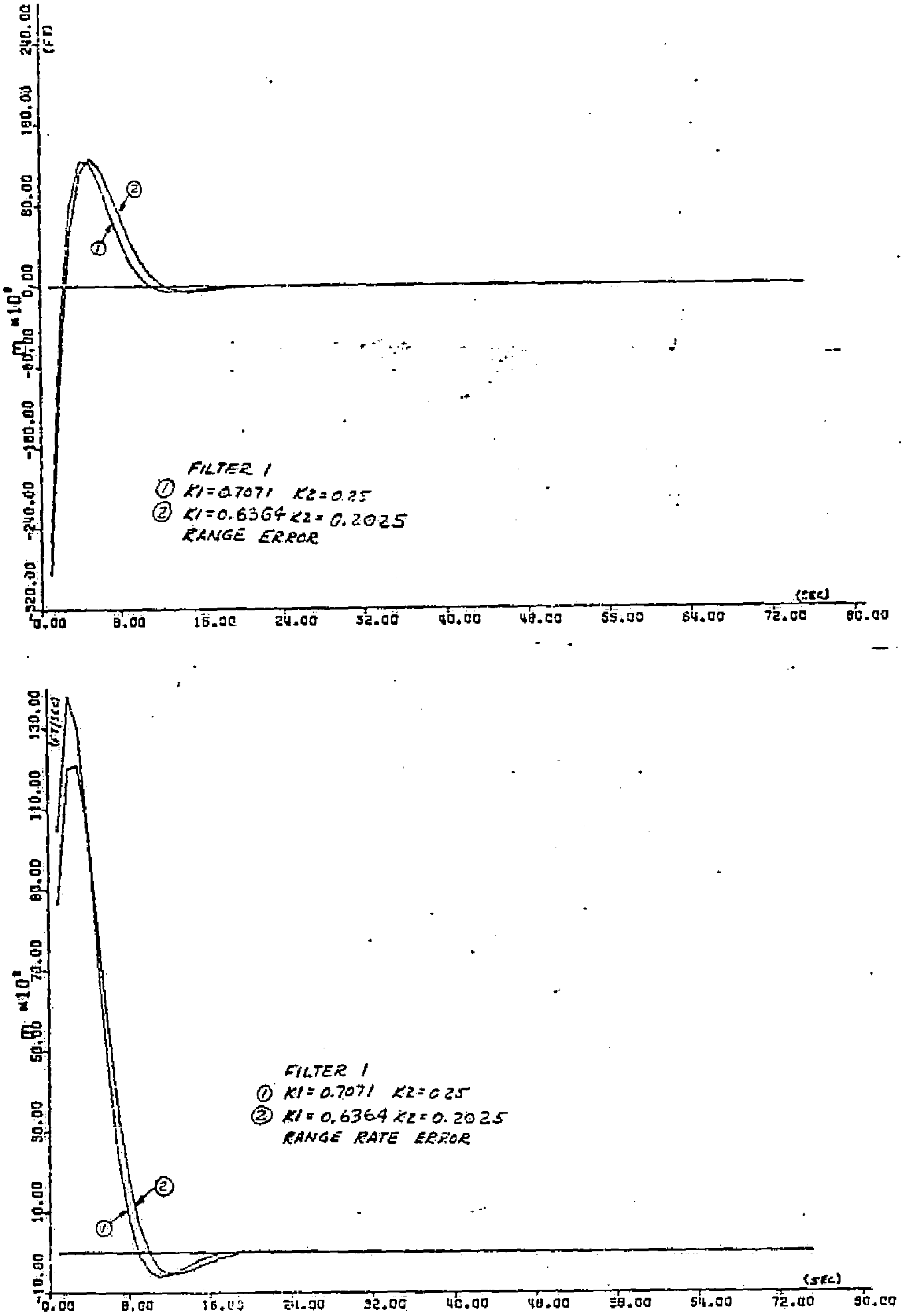


FIGURE 17 - Filter 1 (BLD) at 2500 samples/sec.

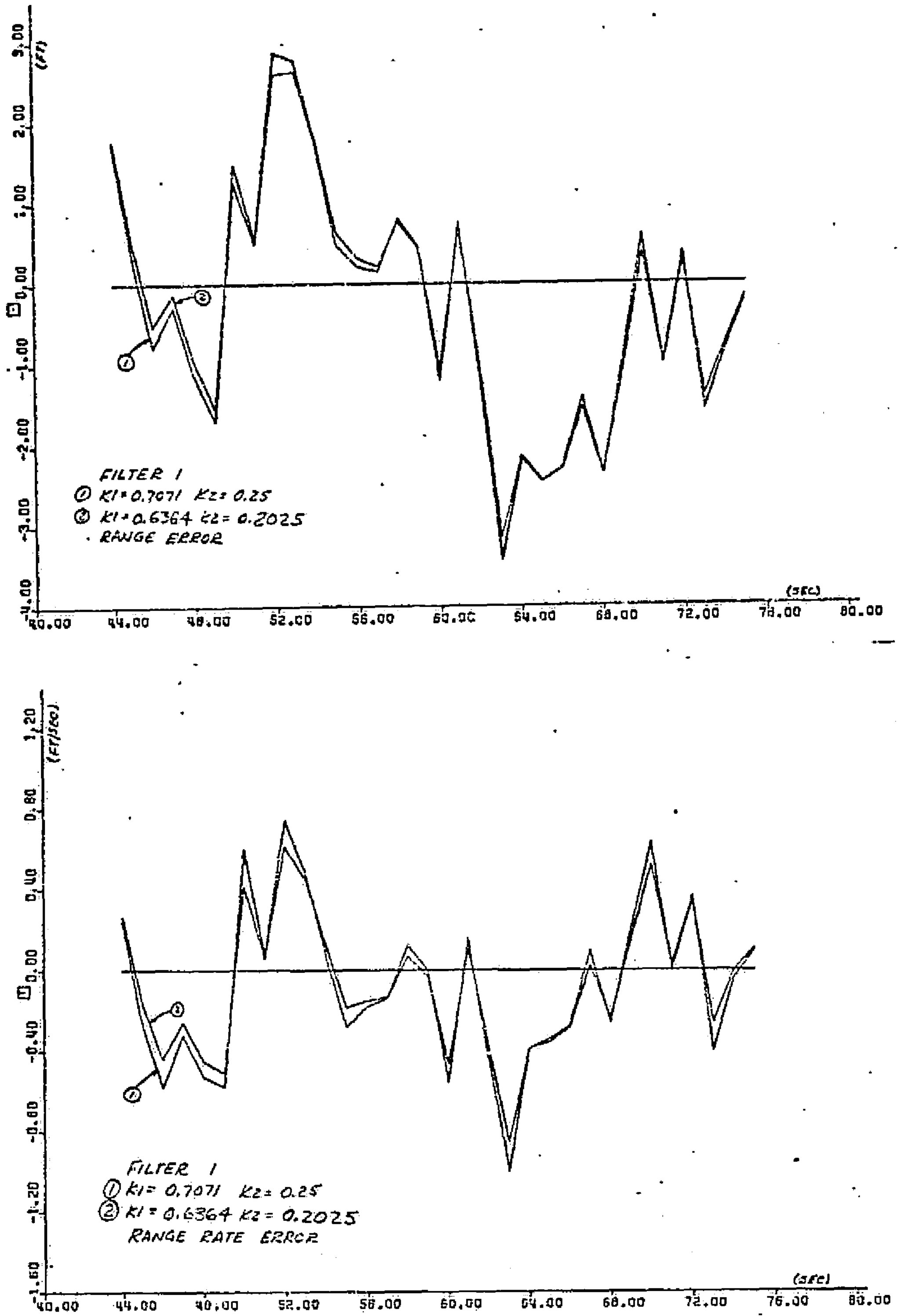


FIGURE 18 - Filter 1 (BLD) at 2500 samples/sec.

TABLE IX

FILTER 1 RANGE STANDARD DEVIATIONS(FT.) AT 6.25 SAMPLES/SEC.

	RUN 1 input = ramp		RUN 2 input = noise		RUN 3 input = ramp + noise	
FILTER 1 CONSTANT GAINS	INPUT RANGE STND. DEV.	OUTPUT RANGE STND. DEV.	INPUT RANGE STND. DEV.	OUTPUT RANGE STND. DEV.	INPUT RANGE STND. DEV.	OUTPUT RANGE STND. DEV.
K1 = 0.7071 K2 = 0.45	65.3068	65.3067	91.3215	24.6606	115.2178	84.4420
K1 = 0.75 K2 = 0.125	65.3068	65.3067	91.3215	19.8742	115.2178	78.3689
K1 = 0.7 K2 = 0.3769	65.3068	65.3067	91.3125	23.6573	115.2178	83.4522
K1 = 0.49 K2 = 0.98995	65.3068	65.3067	91.3125	24.2674	115.2178	82.9028
K1 = 0.75 K2 = 0.45	65.3068	65.3067	91.3215	24.8739	115.2178	84.1560

TABLE X

FILTER 1 RANGE RATE STANDARD DEVIATIONS(FT./SEC.) AT 6.25 SAMPLES/SEC.

FILTER 1 CONSTANT GAINS	RUN 1 input = range OUTPUT RANGE RATE STND. DEV.	RUN 2 input = noise OUTPUT RANGE RATE STND. DEV.	RUN 3 input = ramp + noise OUTPUT RANGE RATE STND. DEV.
K1 = 0.7071 K2 = 0.45	0.0	11.4052	11.4052
K1 = 0.75 K2 = 0.125	0.0	3.2672	3.2671
K1 = 0.7 K2 = 0.3769	0.0	9.8217	9.8218
K1 = 0.49 K2 = 0.98995	0.0	24.8694	24.8694
K1 = 0.75 K2 = 0.45	0.0	11.2231	11.2231

TABLE XI

FILTER 1 MAXIMUM RANGE(FT.) AND RANGE RATE(FT./SEC.) ERRORS AT 6.25 SAMPLES /SEC.

	RUN 1 input = ramp		RUN 2 input = noise		RUN 3 input = ramp + noise	
FILTER 1 CONSTANT GAINS	MAX RANGE ERROR	MAX RANGE RATE ERROR	MAX RANGE ERROR	MAX RANGE RATE ERROR	MAX RANGE ERROR	MAX RANGE RATE ERROR
K1 = 0.7071 K2 = 0.45	4.4800	0.102×10^{-11}	52.8718	28.0303	57.3518	28.0303
K1 = 0.75 K2 = 0.125	4.4800	0.126×10^{-11}	44.8687	5.7304	49.3487	5.7304
K1 = 0.7 K2 = 0.3769	4.4800	0.116×10^{-11}	51.5882	22.9018	56.0682	22.9018
K1 = 0.49 K2 = 0.98995	4.4800	0.483×10^{-12}	57.2146	63.0950	61.6946	63.0950
K1 = 0.75 K2 = 0.45	4.4800	0.112×10^{-11}	53.3341	27.4471	57.8141	27.4471

TABLE XII

FILTER 1 RANGE AND RANGE RATE VARIANCE REDUCTION RATIOS AT 6.25 SAMPLES/SECOND

	RUN 2 input = noise		
FILTER CONSTANT GAINS	KR RANGE VARIANCE REDUCTION RATIO	KRR RANGE RATE VARIANCE REDUCTION RATIO	τ CONVERGENCE TIME (SEC.)
K1 = 0.7071 K2 = 0.45	7.292×10^{-2}	1.560×10^{-2}	23
K1 = 0.75 K2 = 0.125	4.736×10^{-2}	1.280×10^{-3}	36
K1 = 0.7 K2 = 0.3769	6.711×10^{-2}	1.157×10^{-2}	25
K1 = 0.49 K2 = 0.98995	7.062×10^{-2}	7.416×10^{-2}	38
K1 = 0.75 K2 = 0.45	7.419×10^{-2}	1.510×10^{-2}	23

TABLE XIII

FILTER 1 RANGE STANDARD DEVIATIONS(FT.) AT 6.25 SAMPLES/SEC.

	RUN 1 input = ramp		RUN 2 input = noise		RUN 3 input = ramp + noise	
FILTER 1 BLD	INPUT RANGE STND. DEV.	OUTPUT RANGE STND. DEV.	INPUT RANGE STND. DEV.	OUTPUT RANGE STND. DEV.	INPUT RANGE STND. DEV.	OUTPUT RANGE STND. DEV.
K1 = 0.7778 K2 = 0.3025 b = 0.55	65.3068	65.3067	91.3215	23.1994	115.2178	82.0274
K1 = 0.7071 K2 = 0.25 b = 0.50	65.3068	65.3067	91.3215	21.6291	115.2178	81.0868
K1 = 0.6364 K2 = 0.2025 b = 0.45	65.3068	65.3067	91.3215	19.9024	115.2178	79.8818
K1 = 0.5657 K2 = 0.160 b = 0.40	65.3068	65.3067	91.3215	17.9741	115.2178	78.3595
K1 = 0.4950 K2 = 0.1225 b = 0.35	65.3068	65.3067	91.3215	15.7742	115.2178	76.4249

TABLE XIV

FILTER 1 RANGE RATE STANDARD DEVIATIONS(FT./SEC.) AT 6.25 SAMPLES/SEC.

FILTER 1 BLD	RUN 1 input = ramp OUTPUT RANGE RATE STND. DEV.	RUN 2 input = noise OUTPUT RANGE RATE STND. DEV.	RUN 3 input = ramp + noise OUTPUT RANGE RATE STND. DEV.
K1 = 0.7778 K2 = 0.3025 b = 0.55	0.0	7.7822	7.7822
K1 = 0.7071 K2 = 0.25 b = 0.50	0.0	6.7482	6.7482
K1 = 0.6364 K2 = 0.2025 b = 0.45	0.0	5.7662	5.7662
K1 = 0.5657 K2 = 0.160 b = 0.40	0.0	4.8206	4.8206
K1 = 0.4950 K2 = 0.1225 b = 0.35	0.0	3.8874	3.8874

TABLE XV

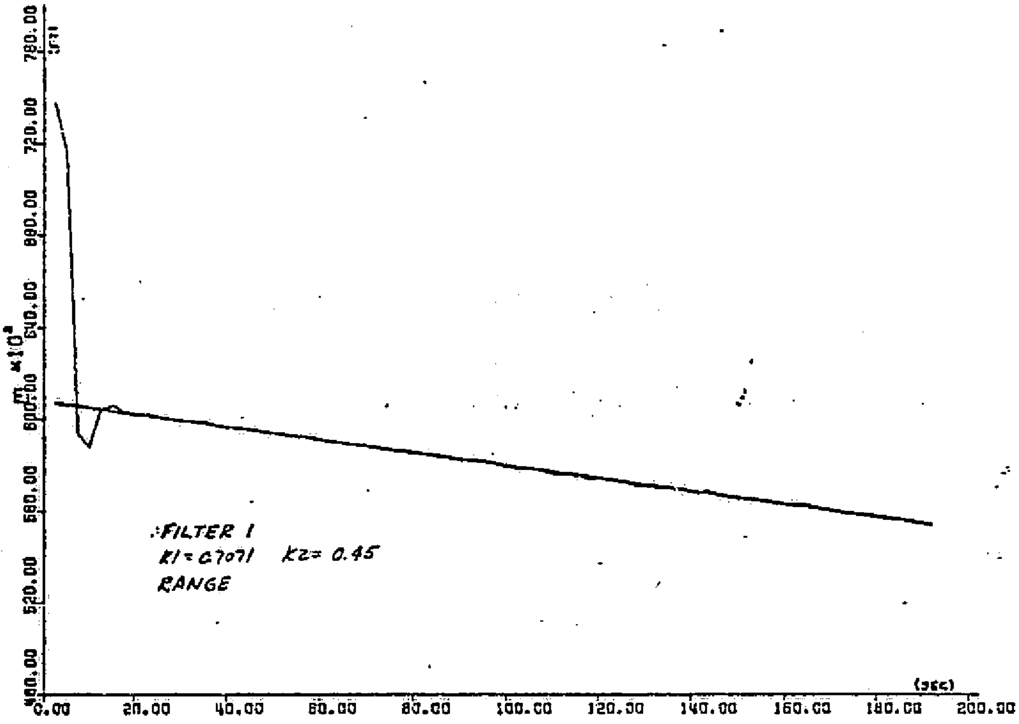
FILTER 1 MAXIMUM RANGE(FT.) AND RANGE RATE(FT./SEC.) ERRORS AT 6.25 SAMPLES/SEC.

	RUN 1		RUN 2		RUN 3	
	input = ramp		input = noise		input = ramp + noise	
FILTER 1 BLD	MAX RANGE ERROR	MAX RANGE RATE ERROR	MAX RANGE ERROR	MAX RANGE RATE ERROR	MAX RANGE ERROR	MAX RANGE RATE ERROR
K1 = 0.7778 K2 = 0.3025 b = 0.55	4.480	0.209×10^{-11}	50.988	16.971	55.468	16.971
K1 = 0.7071 K2 = 0.25 b = 0.50	4.480	0.245×10^{-11}	48.114	13.780	52.594	13.780
K1 = 0.6364 K2 = 0.2125 b = 0.45	4.480	0.270×10^{-11}	44.710	10.906	49.190	10.906
K1 = 0.5657 K2 = 0.160 b = 0.40	4.480	0.329×10^{-11}	40.688	8.570	45.168	8.570
K1 = 0.4950 K2 = 0.1225 b = 0.35	4.480	0.330×10^{-11}	36.010	6.730	40.490	6.730

TABLE XVI

FILTER 1 RANGE AND RANGE RATE VARIANCE REDUCTION RATIOS AT 6.25 SAMPLES/SEC.

	RUN 2 input = noise		
FILTER 1 BLD	KR RANGE VARIANCE REDUCTION RATIO	KRR RANGE RATE VARIANCE REDUCTION RATIO	τ CONVERGENCE TIME (SEC.)
K1 = 0.7778 K2 = 0.3025 b = 0.55	6.454×10^{-2}	7.262×10^{-3}	23
K1 = 0.7071 K2 = 0.25 b = 0.50	5.610×10^{-2}	5.460×10^{-3}	26
K1 = 0.6364 K2 = 0.2025 b = 0.45	4.750×10^{-2}	3.987×10^{-3}	28
K1 = 0.5657 K2 = 0.160 b = 0.40	3.874×10^{-2}	2.770×10^{-3}	31
K1 = 0.4950 K2 = 0.1225 b = 0.35	2.984×10^{-2}	1.812×10^{-3}	36



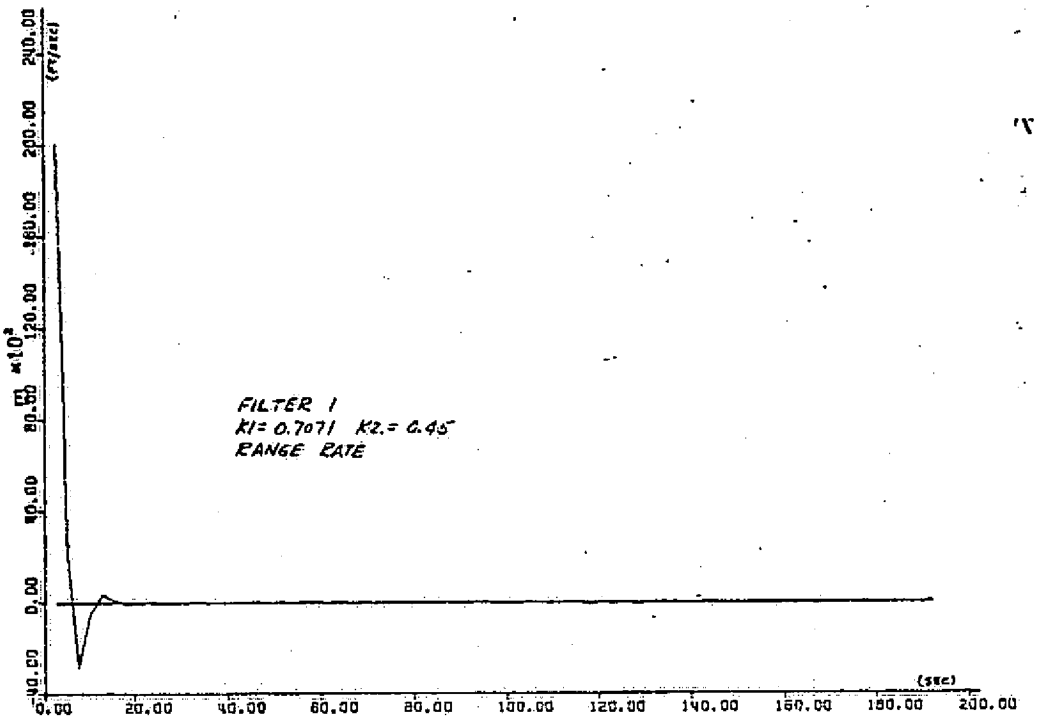


FIGURE 19 - Filter 1 (Constant Gains) at 6.25 samples/sec.

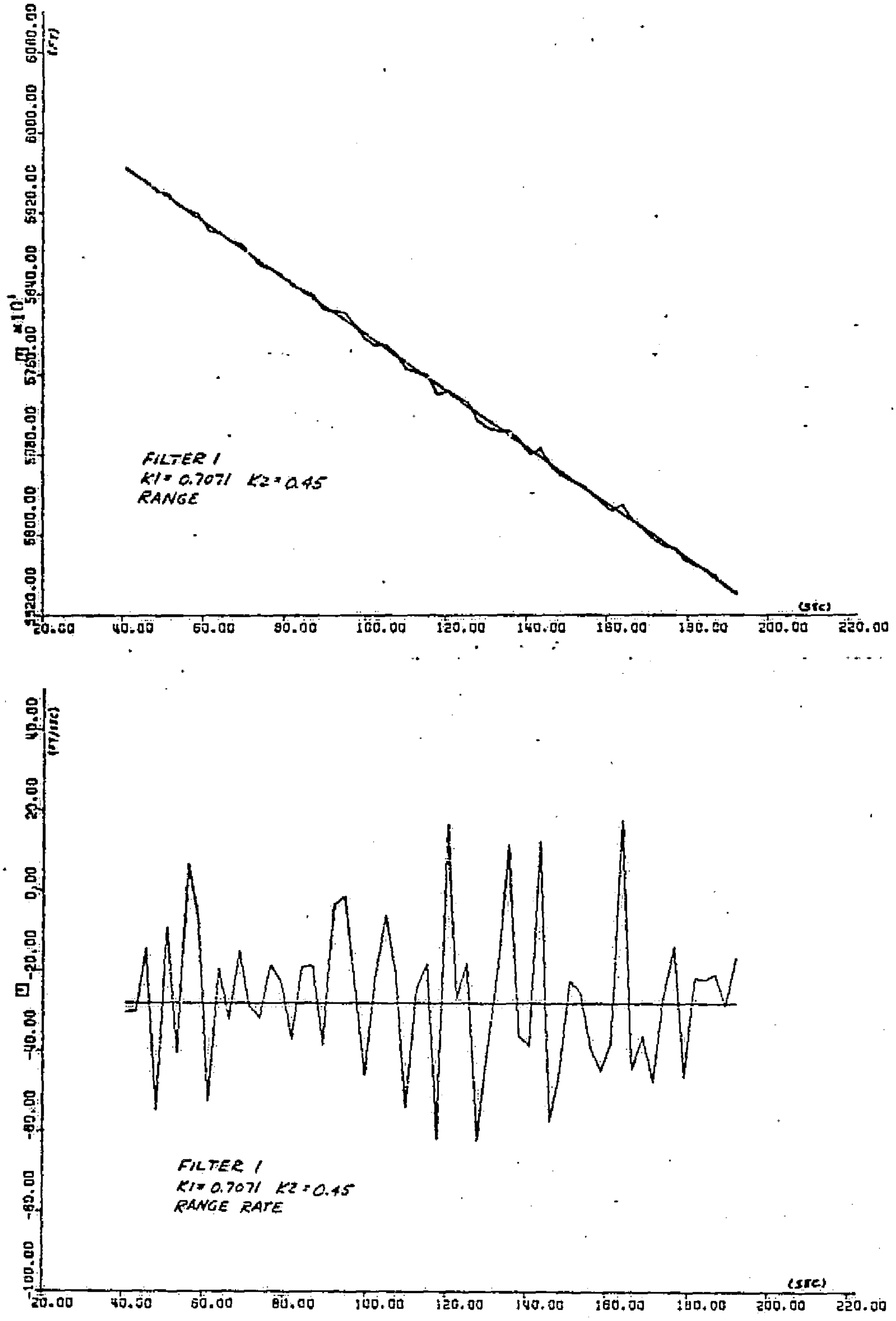


FIGURE 20 - Filter 1 (Constant Gains) at 6.25 samples/sec.

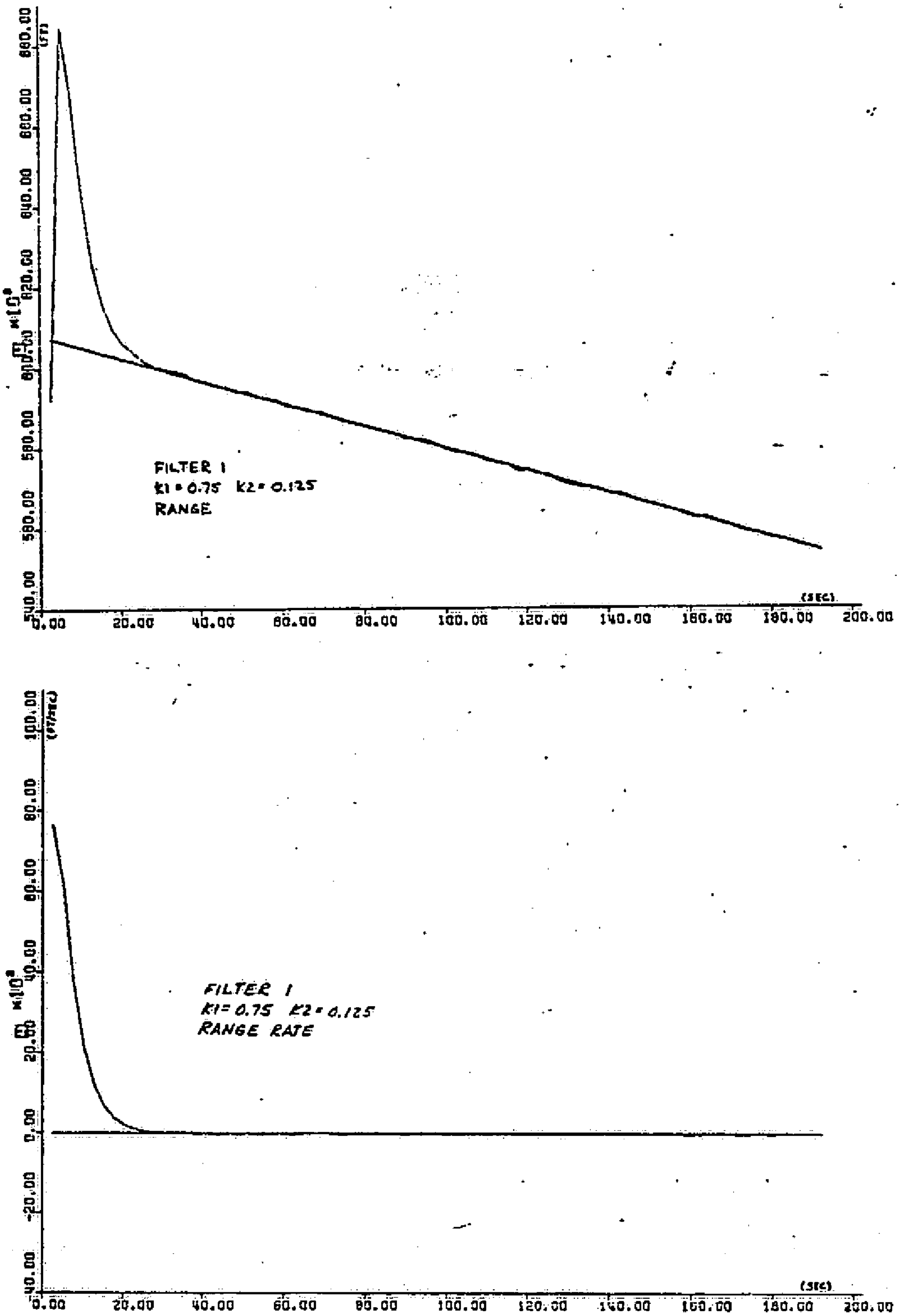


FIGURE 21 - Filter 1 (Constant Gains) at 6.25 samples/sec.

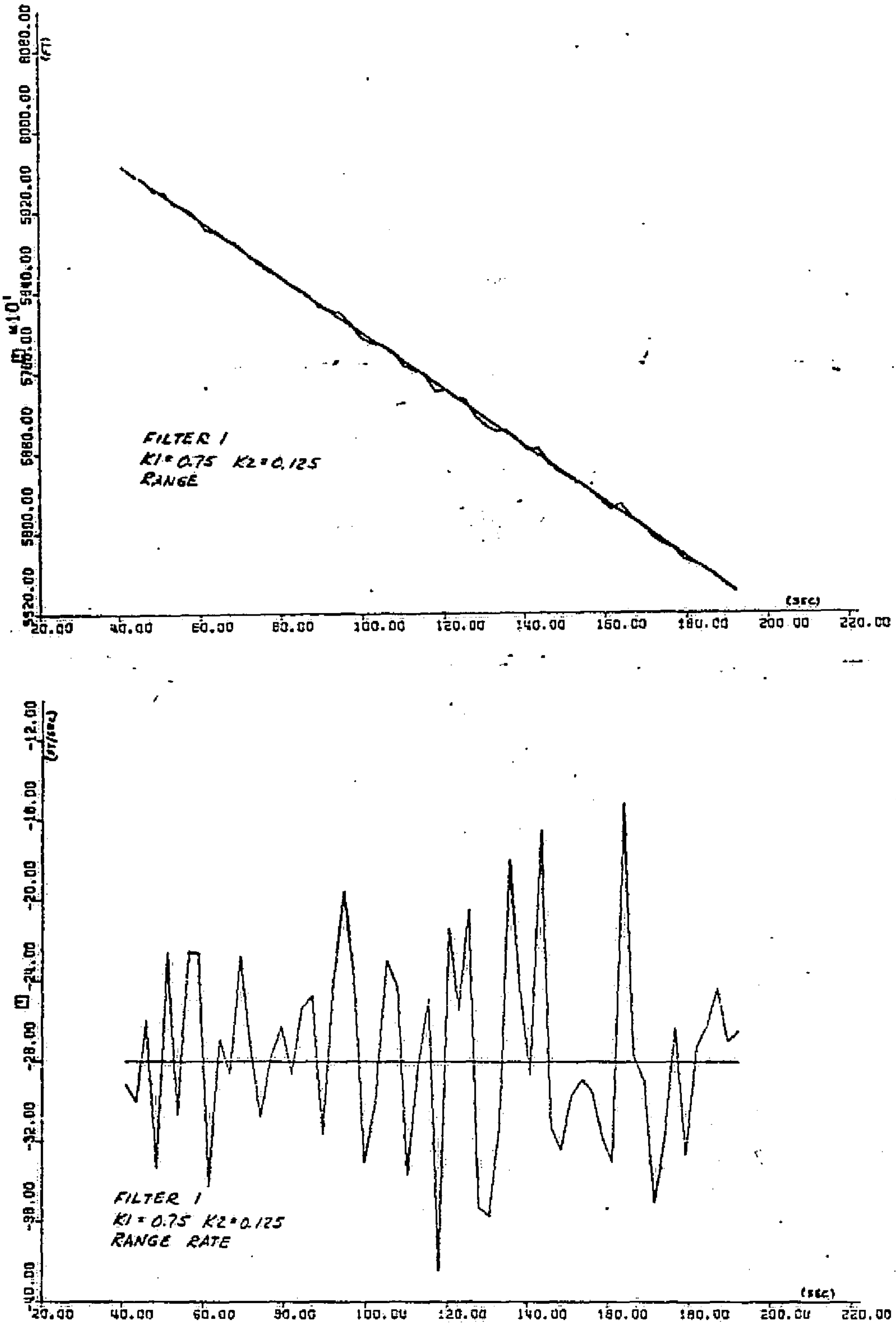


FIGURE 22 - Filter 1 (Constant Gains) at 6.25 samples/sec.

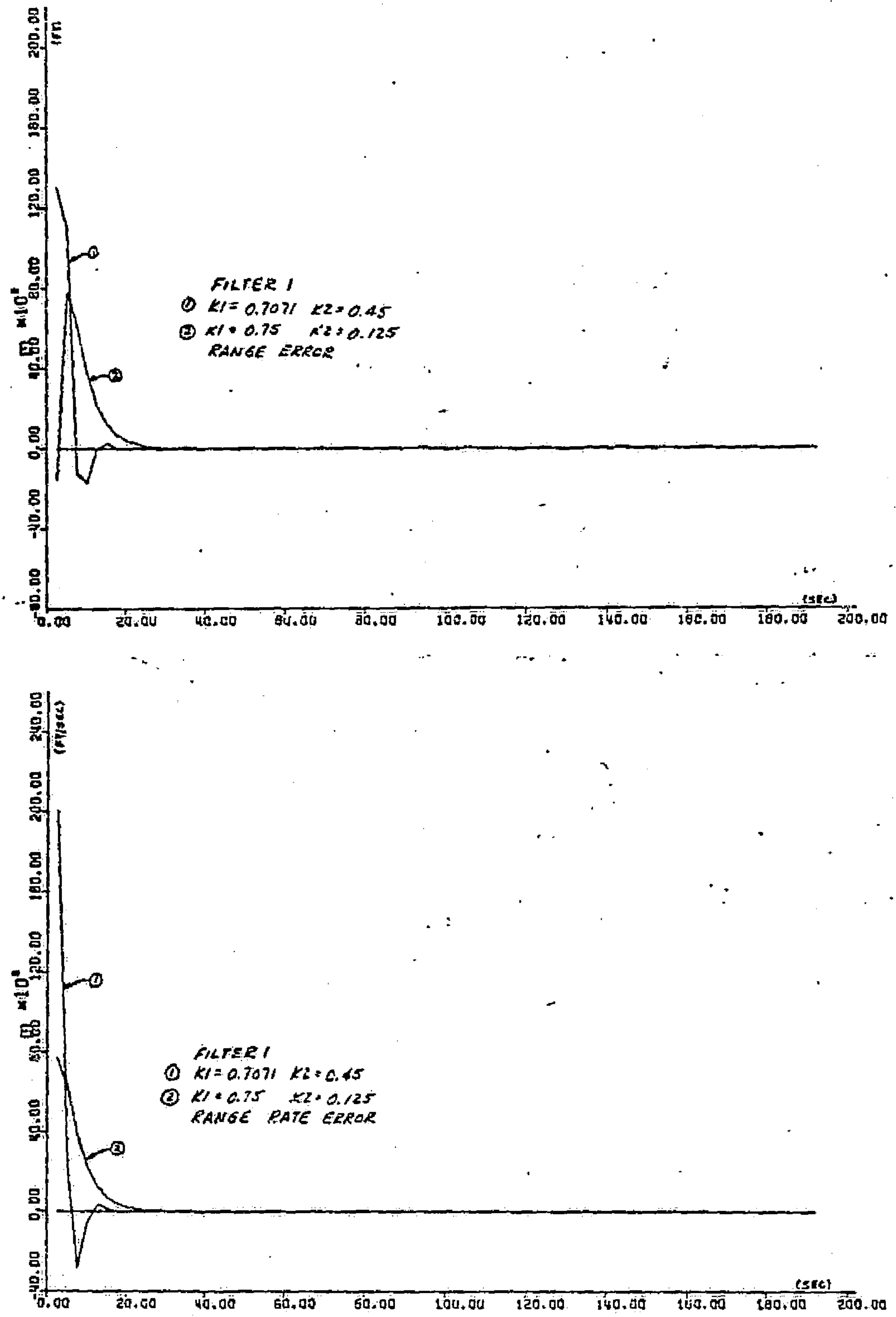


FIGURE 23 - Filter 1 (Constant Gains) at 6.25 samples/sec.

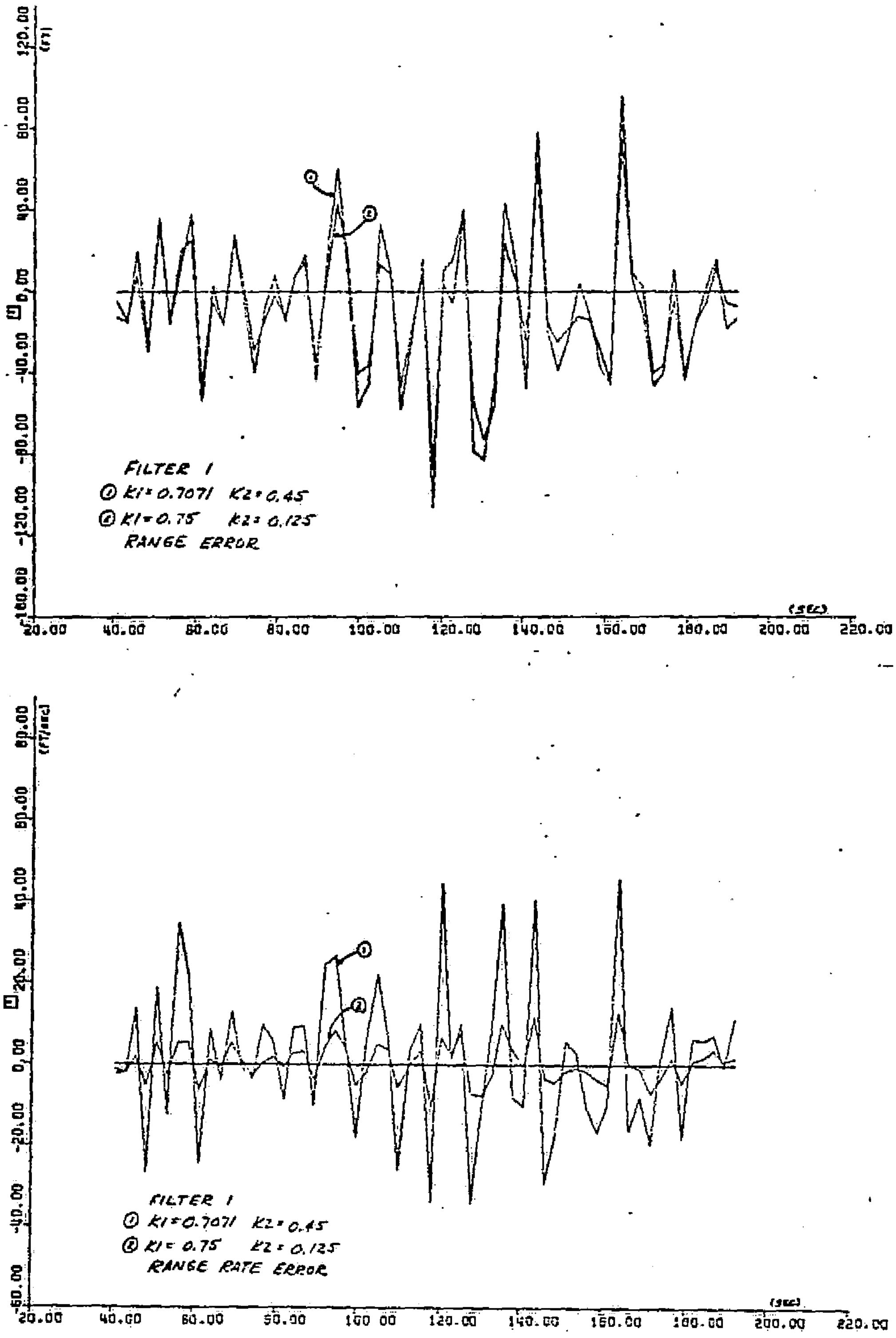


FIGURE 24 - Filter 1 (Constant Gains) at 6.25 samples/sec.

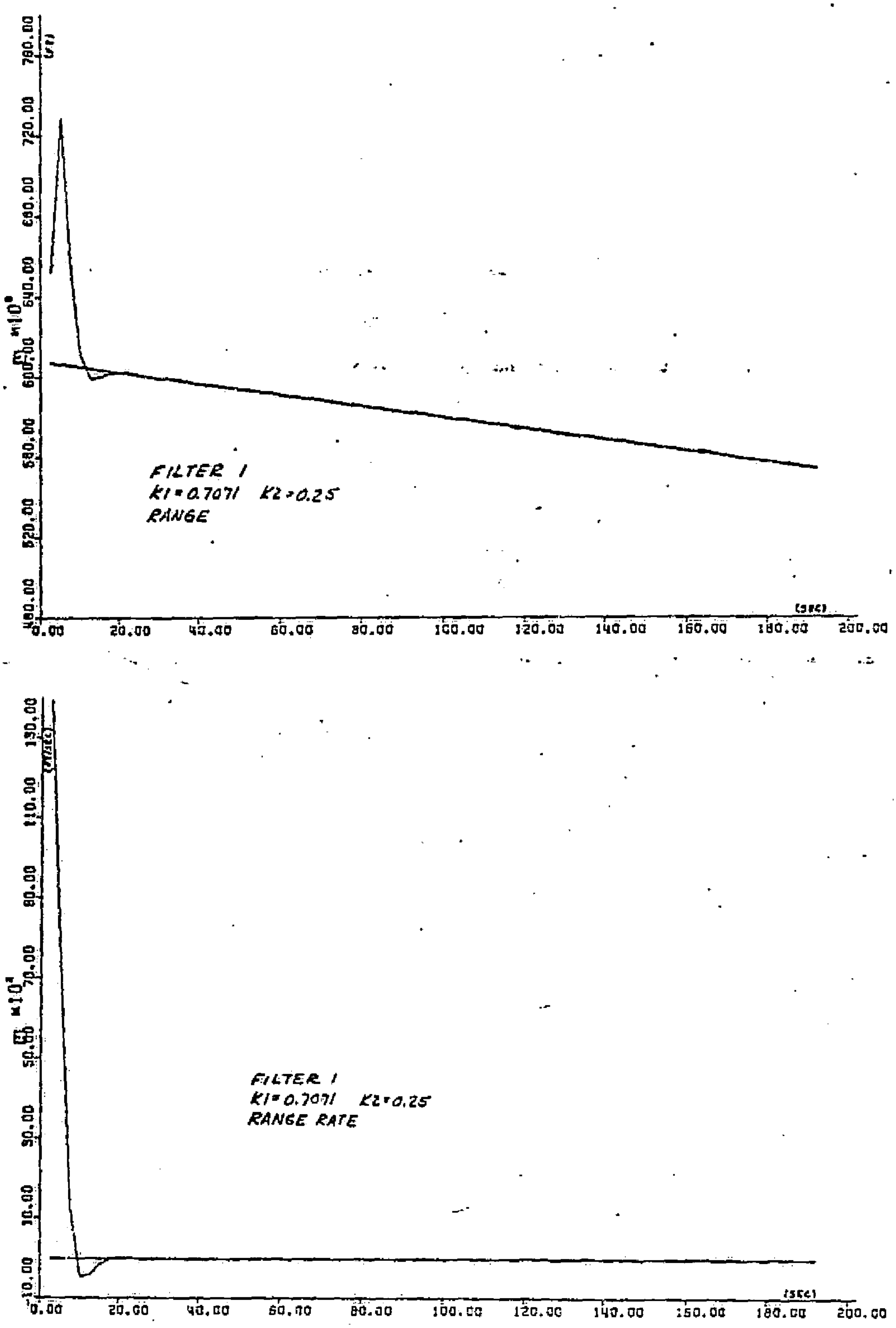


FIGURE 25 - Filter 1 (BLD) at 6.25 samples/sec.

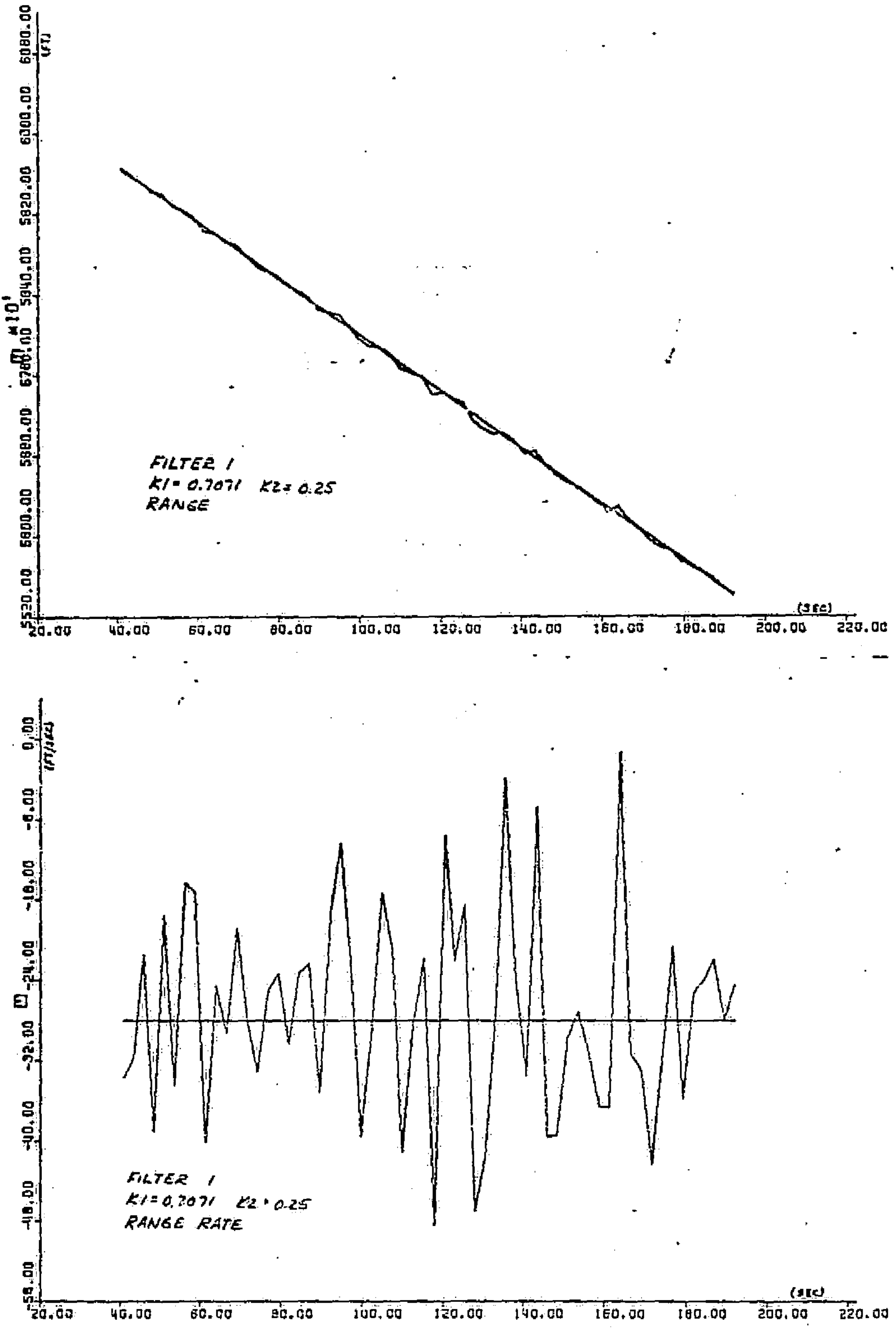


FIGURE 26 - Filter 1 (BLD) at 6.25 samples/sec.

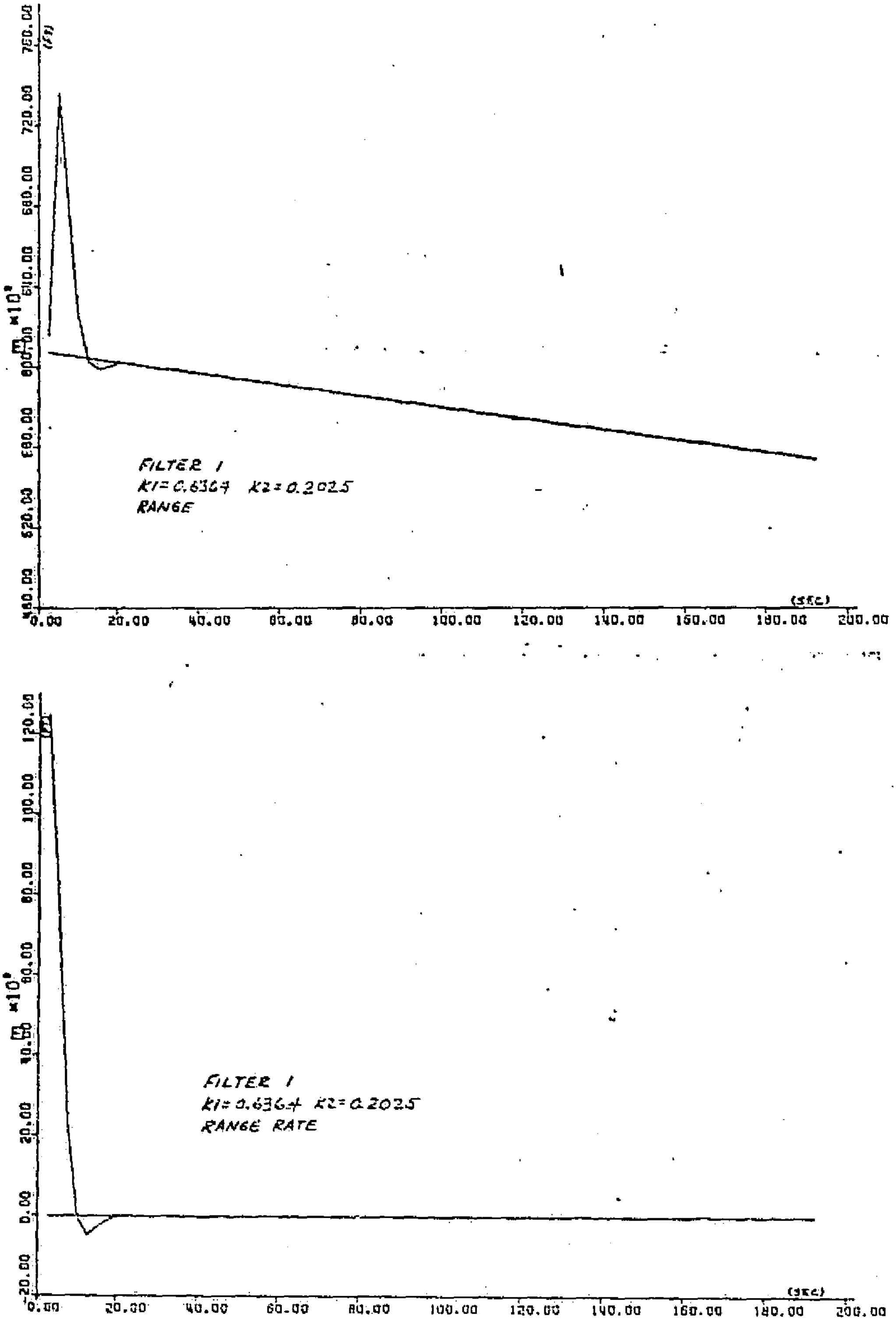


FIGURE 27 - Filter 1 (BLD) at 6.25 samples/sec.

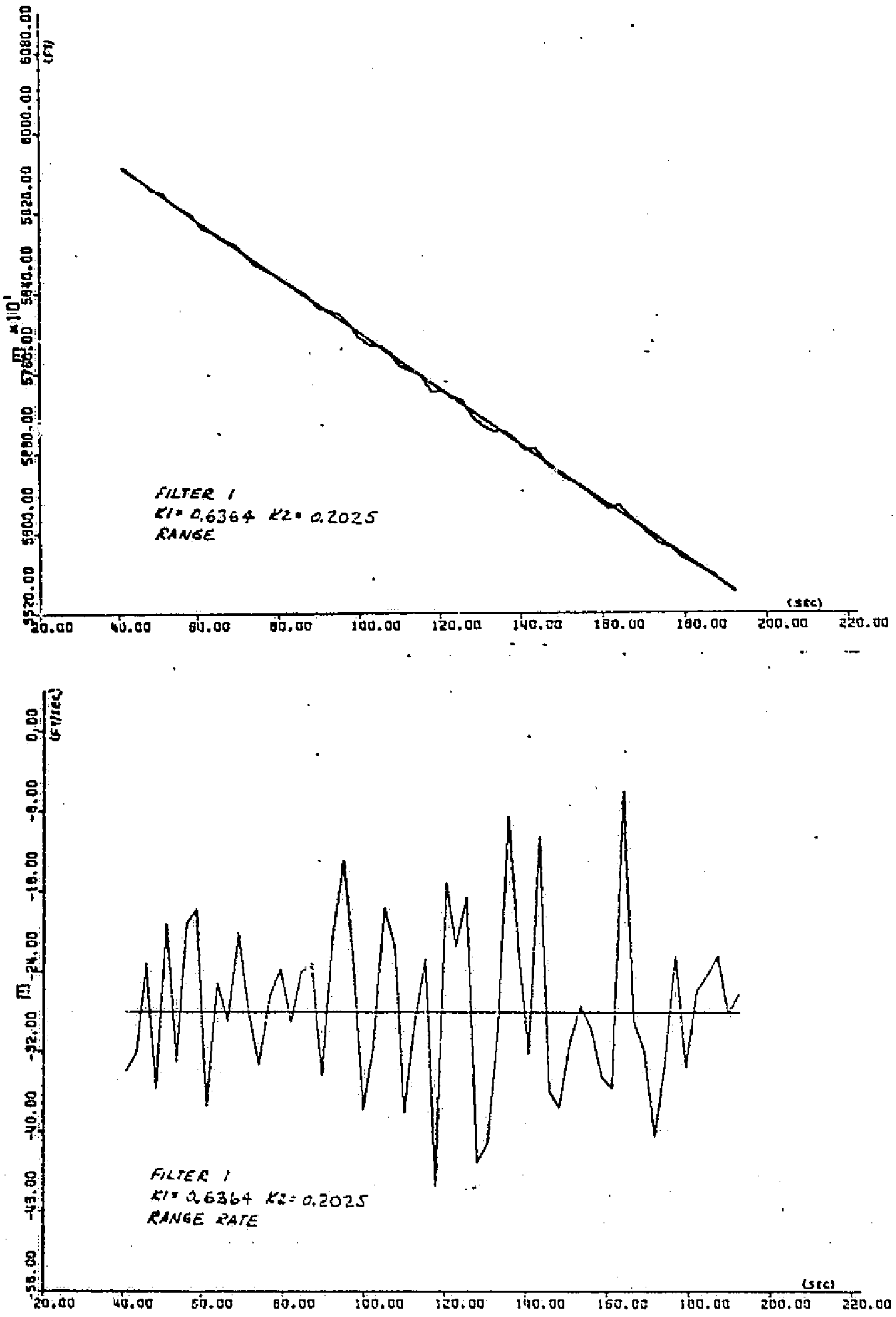


FIGURE 28 - Filter 1 (BLD) at 6.25 samples/sec.

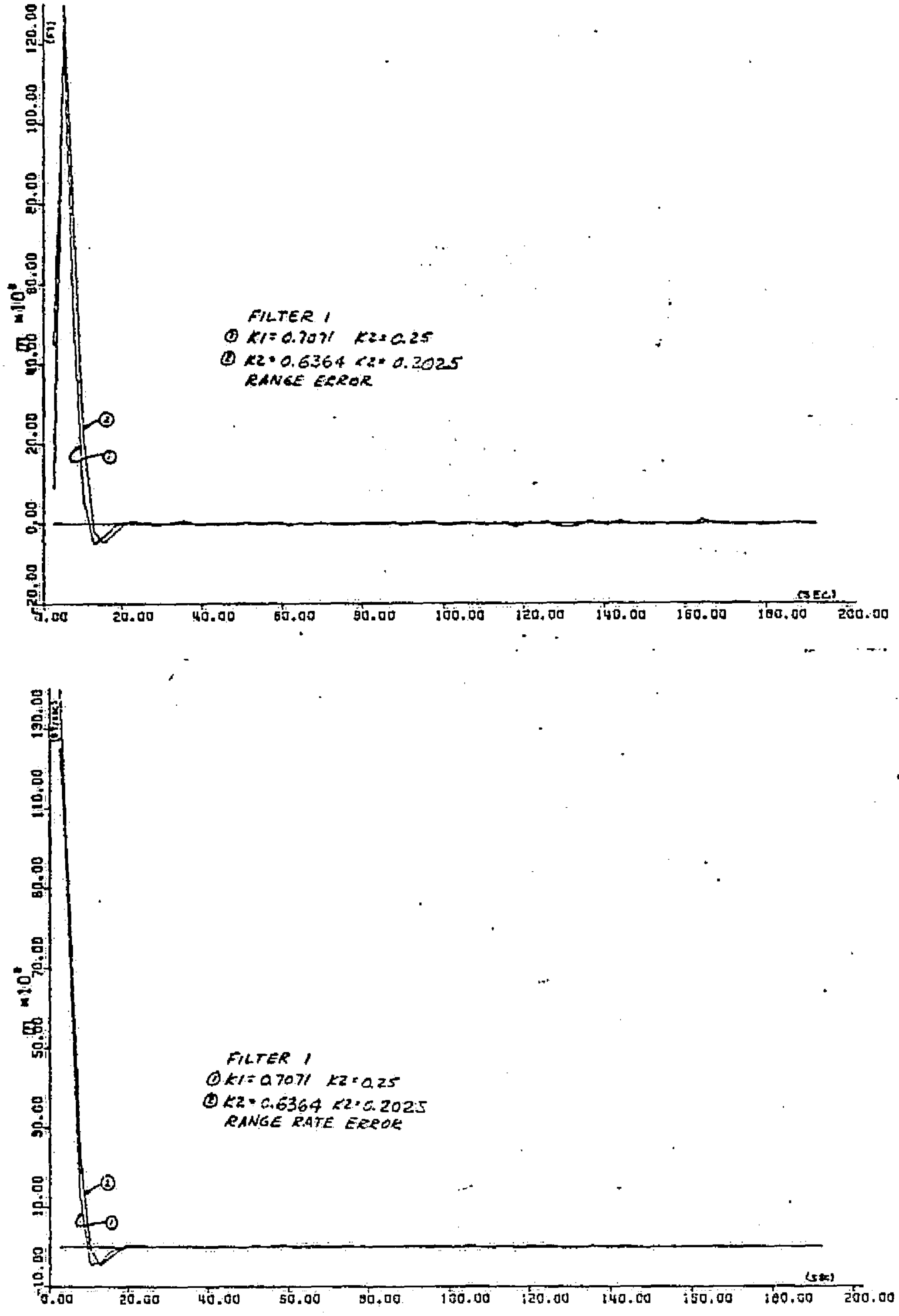
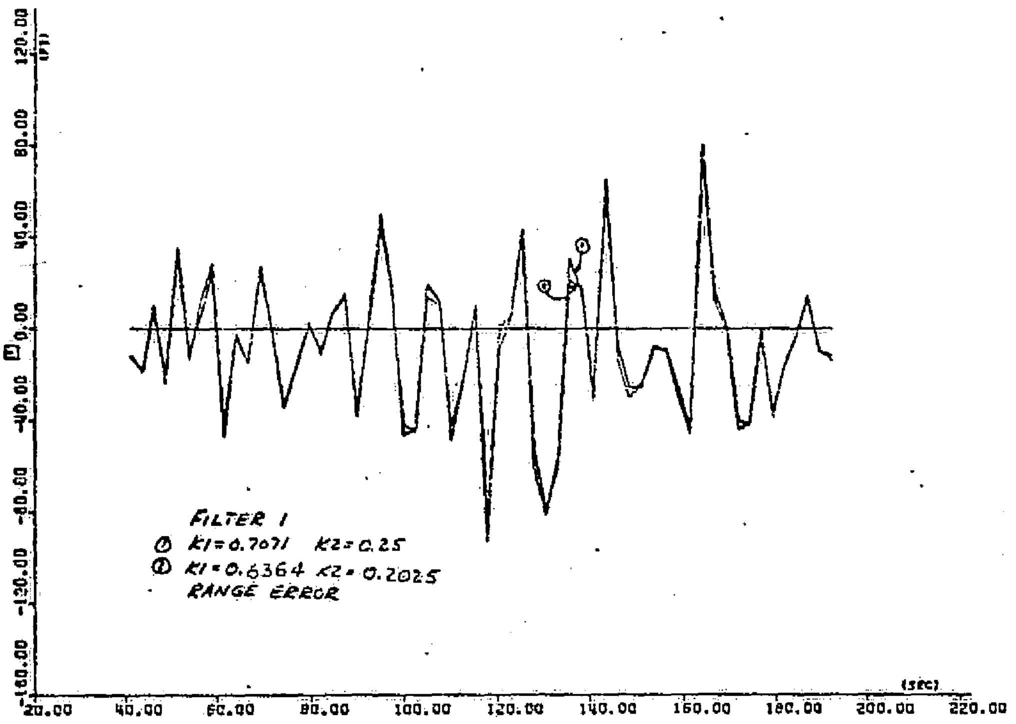


FIGURE 29 - Filter 1 (BLD) at 6.25 samples/sec.



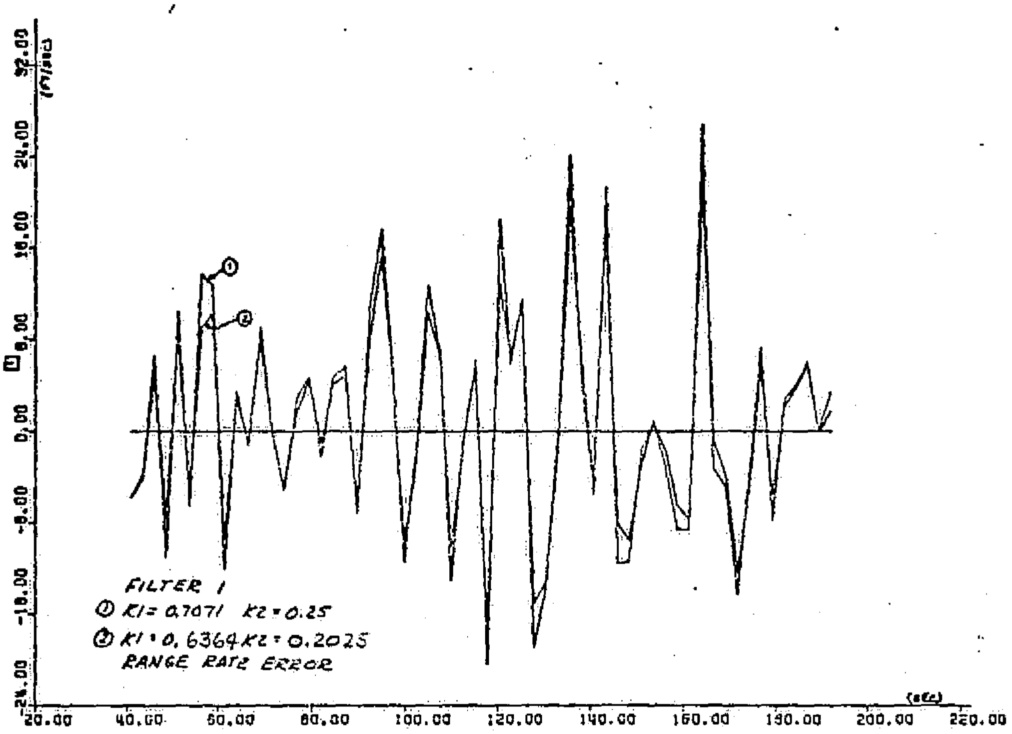


FIGURE 30 - Filter 1 (BLD) at 6.25 samples/sec.

RUN 1. With the ramp input, the recorded range error term represents the change in range over one sampling period. This can be corrected by multiplying the numerator of the transfer function H_R (equation (3)) by the delay term z^{-1}. This has the effect of shifting the system back in time one sampling period. The resulting transfer function is

$$H_R = \frac{RE}{RM} = \frac{z^{-1}(K1DT + K2DT^2) - z^{-2}(K1DT)}{1 + z^{-1}(-2 + K1DT + K2DT^2) + z^{-2}(1 - K1DT)}. \qquad (21)$$

2. <u>Filter 2</u>

Simulation data for Filter 2 is presented in Tables XVII - XX for 2500 samples/second and in Tables XXI - XXIV for the 6.25 samples/second sampling rate. A graphical display of the data is shown for each set of parameter pairs α and β at 2500 samples/second in Figures 31-44. A graphical display of the data for the 6.25 samples/second sampling rate is shown in Figures 45-53. Graphs for two sets of parameter pairs are omitted because they yield systems whose convergence times exceed the duration of the simulation run.

The alpha-beta filter is simulated using six sets of α ,β pairs that lie on the curve described by (10) within the region of stability defined by:

$$\alpha > 0,\ \beta > 0 \text{ and } 2\alpha + \beta < 4. \qquad (22)$$

Near the upper end of the curve, at the point $\alpha = 1.0$ and $\beta = 1.0$, the filter is characterized by fast maneuver-following ability but poor noise rejection. Conversely, near the lower end of the curve, as α and β approach zero, the filter is characterized by improved noise rejection at the expense of maneuver-following ability.

For the 2500 samples/second tests, relative manuever-following capabilities can be determined by examining the convergence time. This is the time required by the filter to recover from the transient at the start of the simulation. For larger values of α (such as $\alpha = 1.0$), convergence time is negligible. However, the range variance reduction ratio (KR) is one, meaning there is no noise attenuation. As α and β are decreased, convergence time increases indicating the inertia of the system is increasing and more time is required to recover from transients. While this presents a reduction in maneuver-following capabilities it also means the system is becoming more insensitive to the higher frequency components of noise. Hence, there is a corresponding decrease in range and range rate variance reduction ratios.

These observations are even more readily seen in the 6.25 samples/second simulation runs. The reduction in sampling rate causes an increase in convergence time. As an example, for $\alpha = 0.05$ and $\beta = 1.282 \times 10^{-2}$, the convergence time at 2500 samples/second is less than one second. However, at 6.25 samples/second that figure is approximately 56 seconds. In fact, the last three entries in the tables for the 6.25 samples/second tests all represent α,β pairs whose convergence times exceed the 192

TABLE XVII

FILTER 2 RANGE STANDARD DEVIATIONS(FT.) AT 2500 SAMPLES/SEC.

FILTER 2 alpha - beta	RUN 1 input = ramp		RUN 2 input = noise		RUN 2 input = ramp + noise	
	INPUT RANGE STND. DEV.	OUTPUT RANGE STND. DEV.	INPUT RANGE STND. DEV.	OUTPUT RANGE STND. DEV.	INPUT RANGE STND. DEV.	OUTPUT RANGE STND. DEV.
$\alpha = 1.0$ $\beta = 1.0$	0.1634	0.1634	110.7364	110.7364	110.7339	110.7339
$\alpha = 0.2$ $\beta = 0.022222$	0.1634	0.1634	110.7364	29.0844	110.7339	29.0377
$\alpha = 0.05$ $\beta = 0.1282 \times 10^{-2}$	0.1634	0.1634	110.7364	7.5559	110.7339	7.6332
$\alpha = 0.001$ $\beta = 5.0025 \times 10^{-7}$	0.1634	0.1634	110.7364	0.3205	110.7339	0.4751
$\alpha = 0.00030$ $\beta = 4.50067 \times 10^{-8}$	0.1634	0.1634	110.7364	0.9379×10^{-1}	110.7339	0.2518
$\alpha = 0.00021$ $\beta = 2.20523 \times 10^{-8}$	0.1634	0.1632	110.7364	0.6538×10^{-1}	110.7339	0.225

TABLE XVIII

FILTER 2 RANGE RATE STANDARD DEVIATIONS(FT./SEC.) AT 2500 SAMPLES/SEC.

	RUN 1	RUN 2	RUN 3
	input = ramp	input = noise	input = ramp + noise
FILTER 2 alpha - beta	OUTPUT RANGE RATE STND. DEV.	OUTPUT RANGE RATE STND. DEV.	OUTPUT RANGE RATE STND. DEV.
$\alpha = 1.0$ $\beta = 1.0$	0.0	412275.80	412275.81
$\alpha = 0.2$ $\beta = 0.0222222$	0.0	8741.49	8741.49
$\alpha = 0.05$ $\beta = 0.1282 \times 10^{-2}$	0.0	445.064	445.0637
$\alpha = 0.001$ $\beta = 5.0025 \times 10^{-7}$	0.0	0.3965	0.3965
$\alpha = 0.00030$ $\beta = 4.50067 \times 10^{-8}$	0.0	0.3550×10^{-1}	0.355×10^{-1}
$\alpha = 0.00021$ $\beta = 2.20523 \times 10^{-8}$	0.0	0.1739×10^{-1}	0.1739×10^{-1}

TABLE XIX

FILTER 2 MAXIMUM RANGE(FT.) AND RANGE RATE(FT./SEC.) ERRORS AT 2500 SAMPLES/SEC.

	RUN 1 input = ramp		RUN 2 input = noise		RUN 3 input = ramp + noise	
FILTER 2 alpha - beta	MAX RANGE ERROR	MAX RANGE RATE ERROR	MAX RANGE ERROR	MAX RANGE RATE ERROR	MAX RANGE ERROR	MAX RANGE RATE ERROR
$\alpha = 1.0$ $\beta = 1.0$	0.0	0.578×10^{-9}	254.932	989103.5	254.932	989103.5
$\alpha = 0.2$ $\beta = 0.022222$	0.0	0.226×10^{-10}	96.237	21226.7	96.237	21226.7
$\alpha = 0.05$ $\beta = 0.1282 \times 10^{-2}$	0.909×10^{-12}	0.476×10^{-9}	37.824	1792.05	37.824	1792.05
$\alpha = 0.001$ $\beta = 5.0025 \times 10^{-7}$	0.546×10^{-10}	0.166×10^{-8}	0.780	1.409	0.780	1.409
$\alpha = 0.00030$ $\beta = 4.50067 \times 10^{-8}$	0.425×10^{-7}	0.414×10^{-8}	0.199	0.236	0.199	0.236
$\alpha = 0.00021$ $\beta = 2.20523 \times 10^{-8}$	0.134×10^{-4}	0.670×10^{-4}	0.133	0.194	0.133	0.194

TABLE XX

FILTER 2 RANGE AND RANGE RATE VARIANCE REDUCTION RATIOS AT 2500 SAMPLES/SEC.

	RUN 2 input = noise		PREDICTED BY BENEDICT AND BORDNER		
FILTER 2 alpha - beta	KR RANGE VARIANCE REDUCTION RATIO	KRR RANGE RATE VARIANCE REDUCTION RATIO	KR	KRR	τ CONVERGENCE TIME (SEC.)
$\alpha = 1.0$ $\beta = 1.0$	1.0	1.386×10^{7}	1.0	1.25×10^{7}	<1
$\alpha = 0.2$ $\beta = 0.022222$	6.898×10^{-2}	6.231×10^{3}	1.534×10^{-1}	8.521×10^{3}	<1
$\alpha = 0.05$ $\beta = 0.1282 \times 10^{-2}$	4.656×10^{-3}	1.615×10^{1}	3.782×10^{-2}	1.056×10^{2}	<1
$\alpha = 0.001$ $\beta = 5.0025 \times 10^{-7}$	8.377×10^{-6}	1.282×10^{-5}	7.501×10^{-4}	7.824×10^{-4}	8
$\alpha = 0.00030$ $\beta = 4.50067 \times 10^{-8}$	7.174×10^{-7}	1.028×10^{-7}	2.250×10^{-4}	2.110×10^{-5}	24
$\alpha = 0.00021$ $\beta = 2.20523 \times 10^{-8}$	3.486×10^{-7}	2.466×10^{-8}	1.575×10^{-4}	7.237×10^{-6}	35

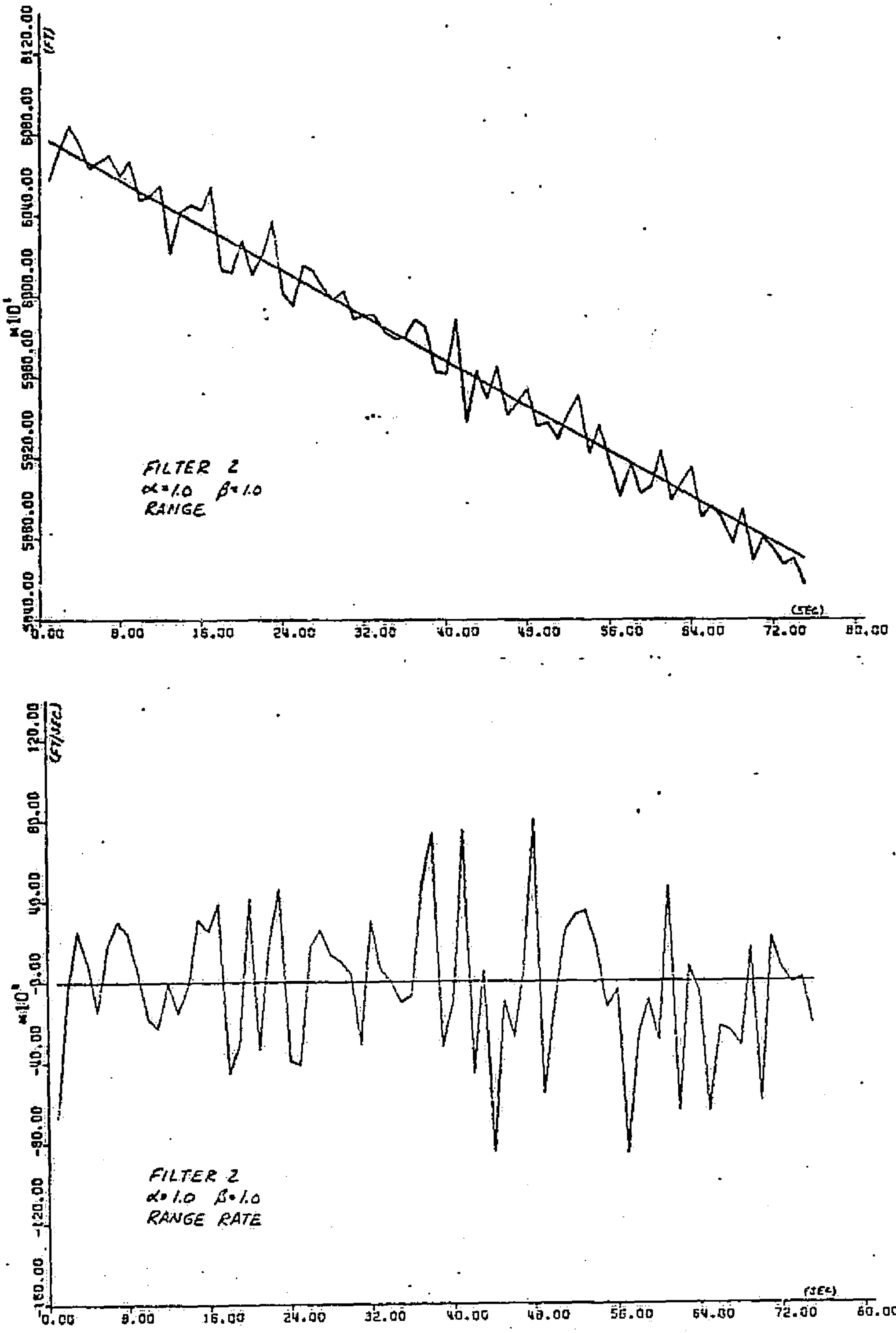


FIGURE 31 - Filter 2 at 2500 samples/sec.

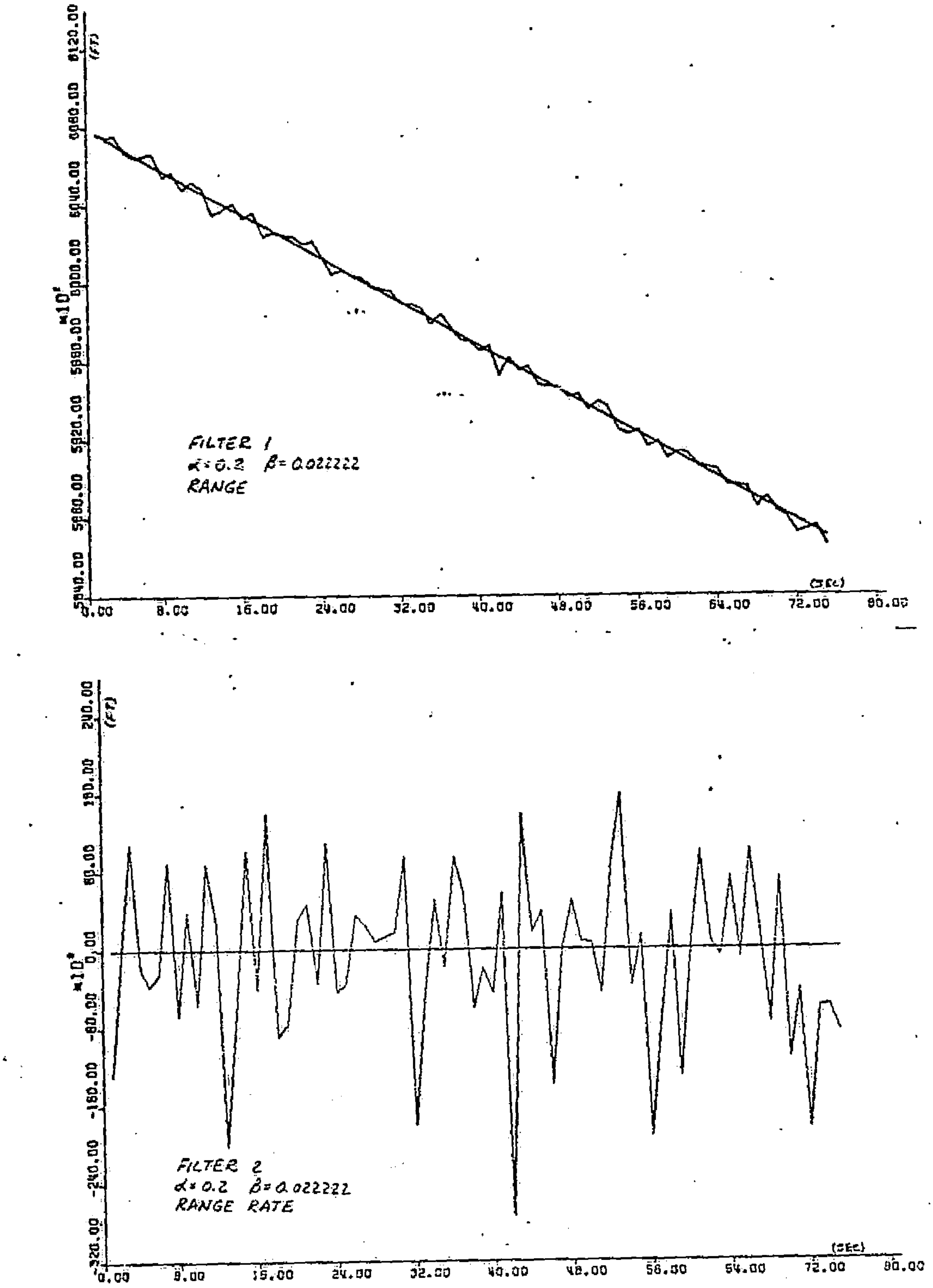


FIGURE 32 - Filter 2 at 2500 samples/sec.

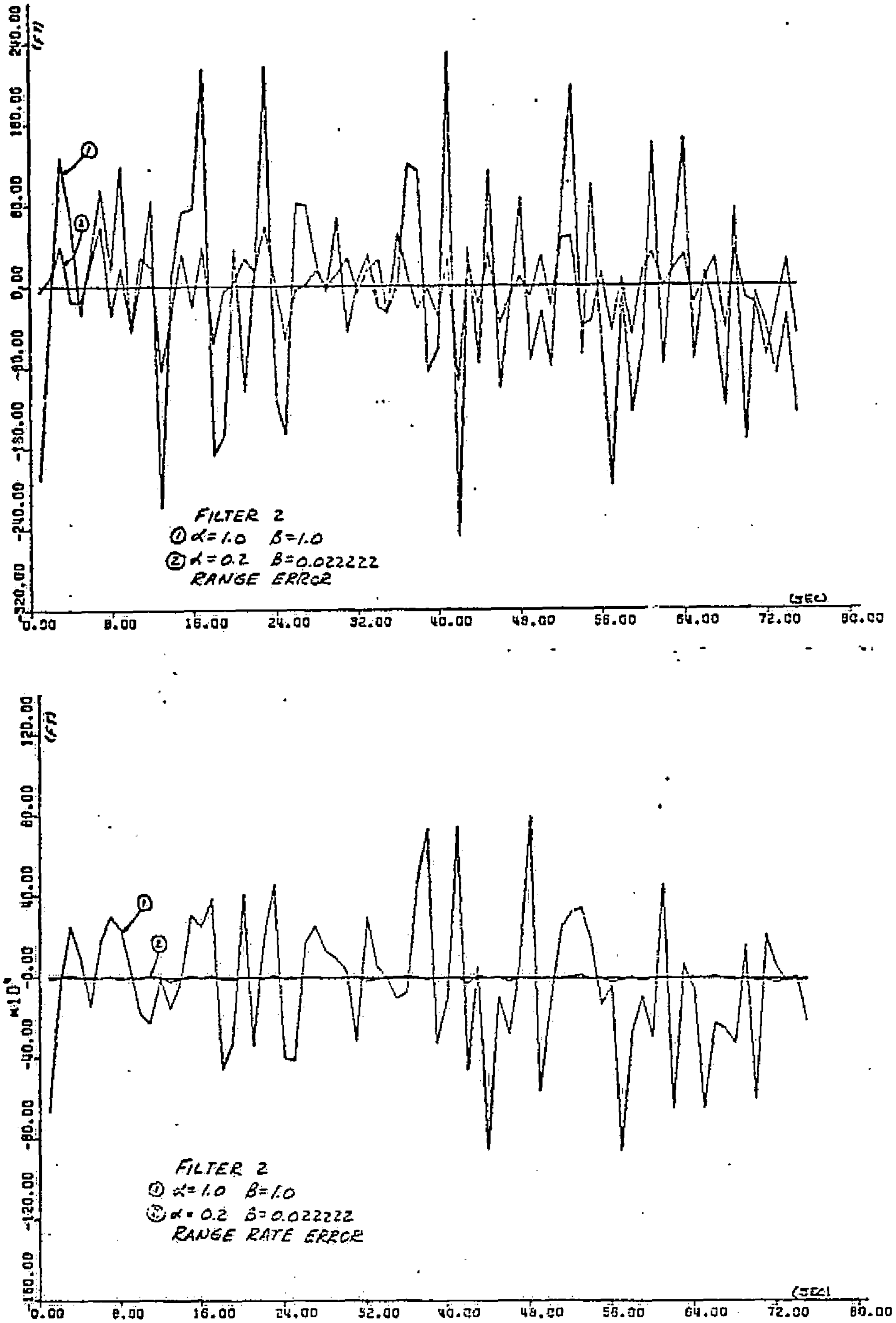


FIGURE 33 - Filter 2 at 2500 samples/sec.

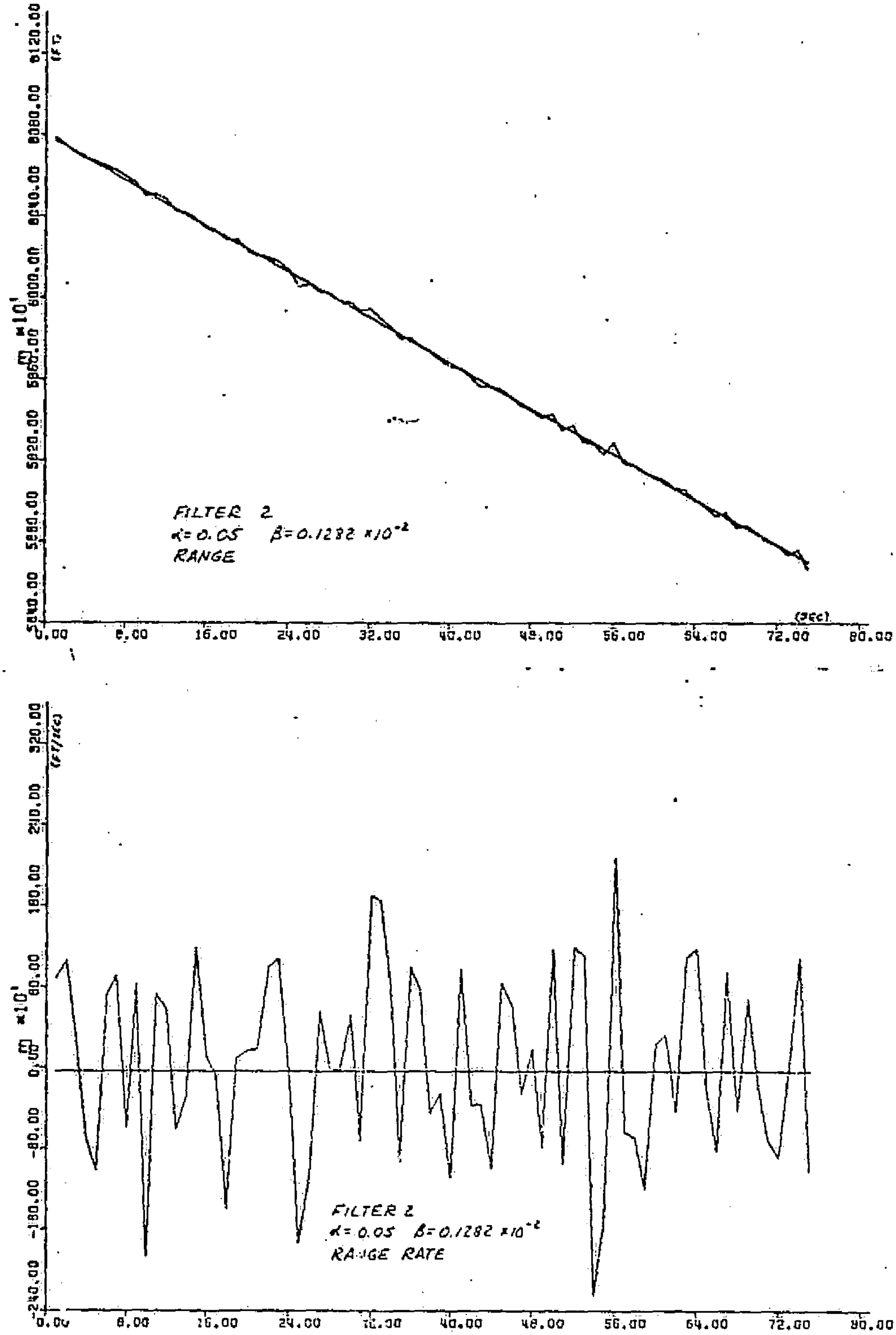


FIGURE 34 - Filter 2 at 2500 samples/sec.

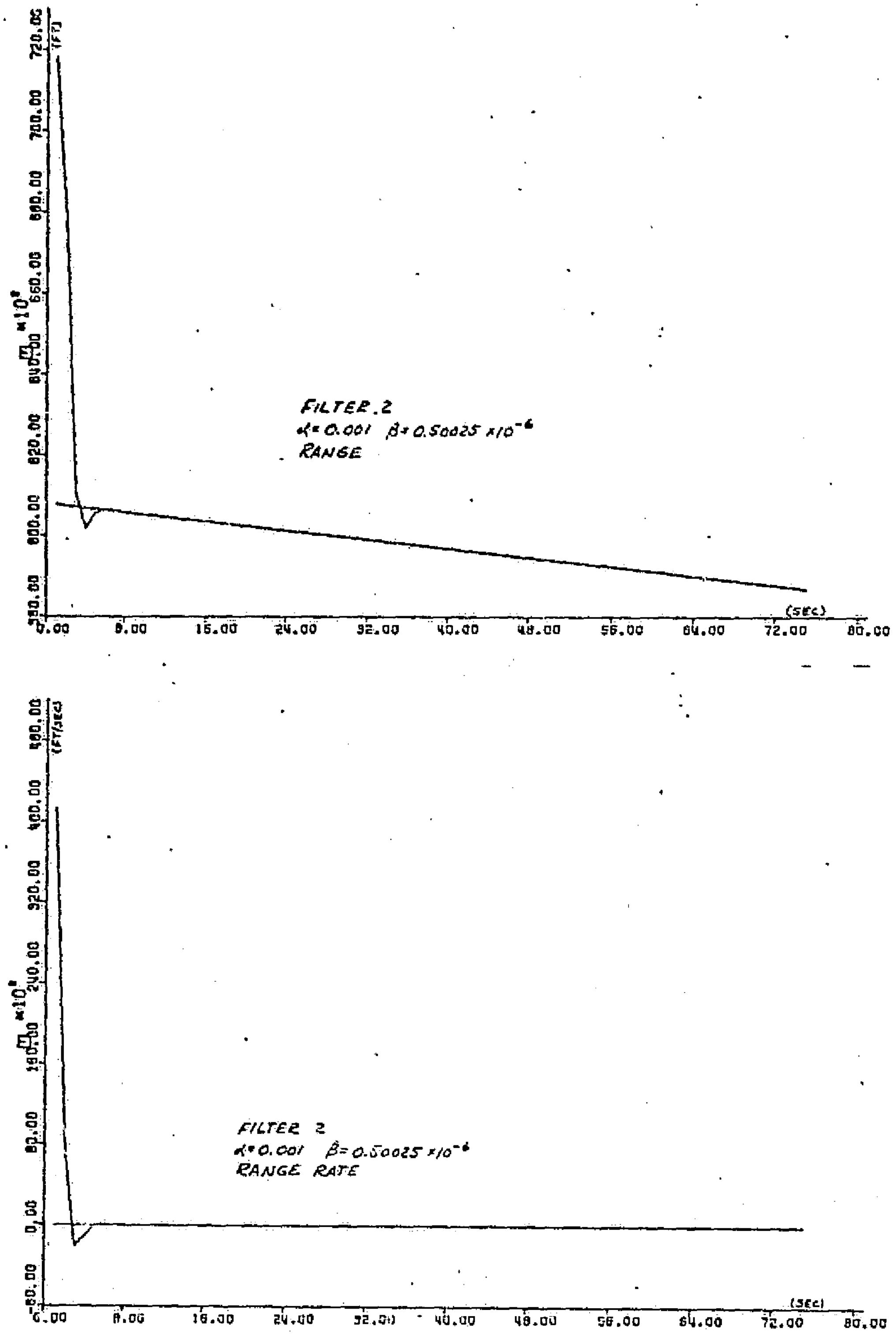


FIGURE 35 - Filter 2 at 2500 samples/sec.

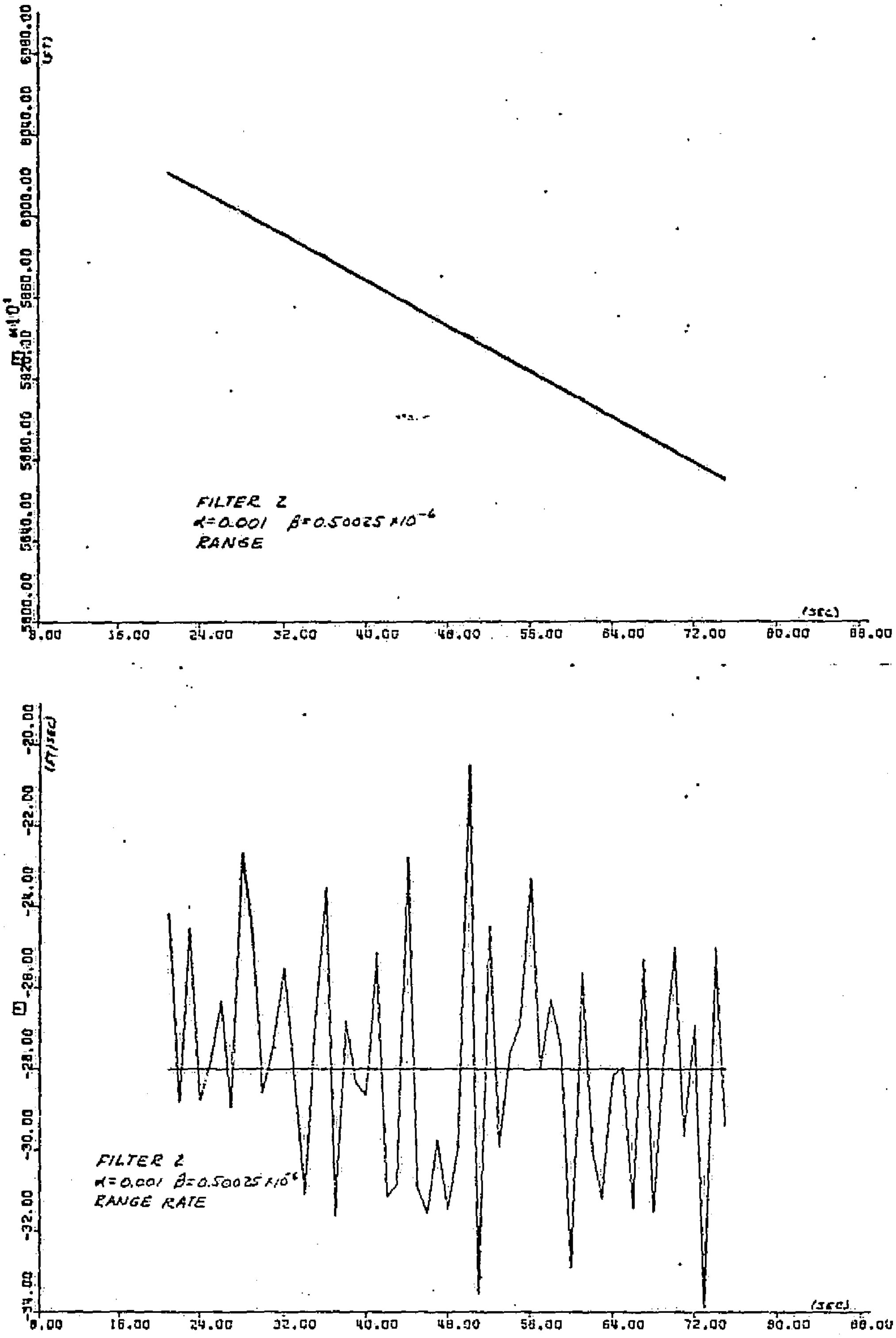


FIGURE 36 - Filter 2 at 2500 samples/sec.

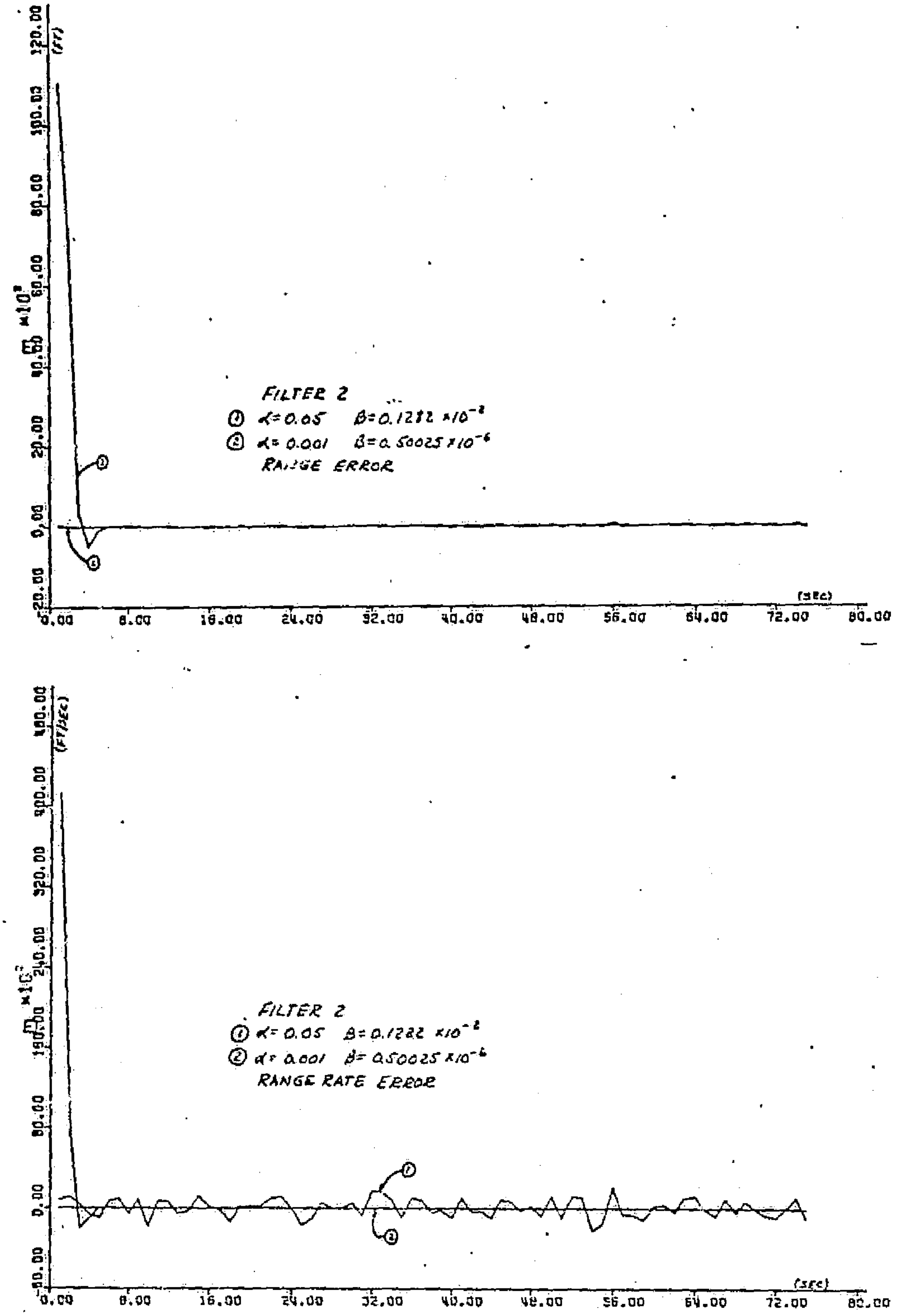


FIGURE 37 - Filter 2 at 2500 samples/sec.

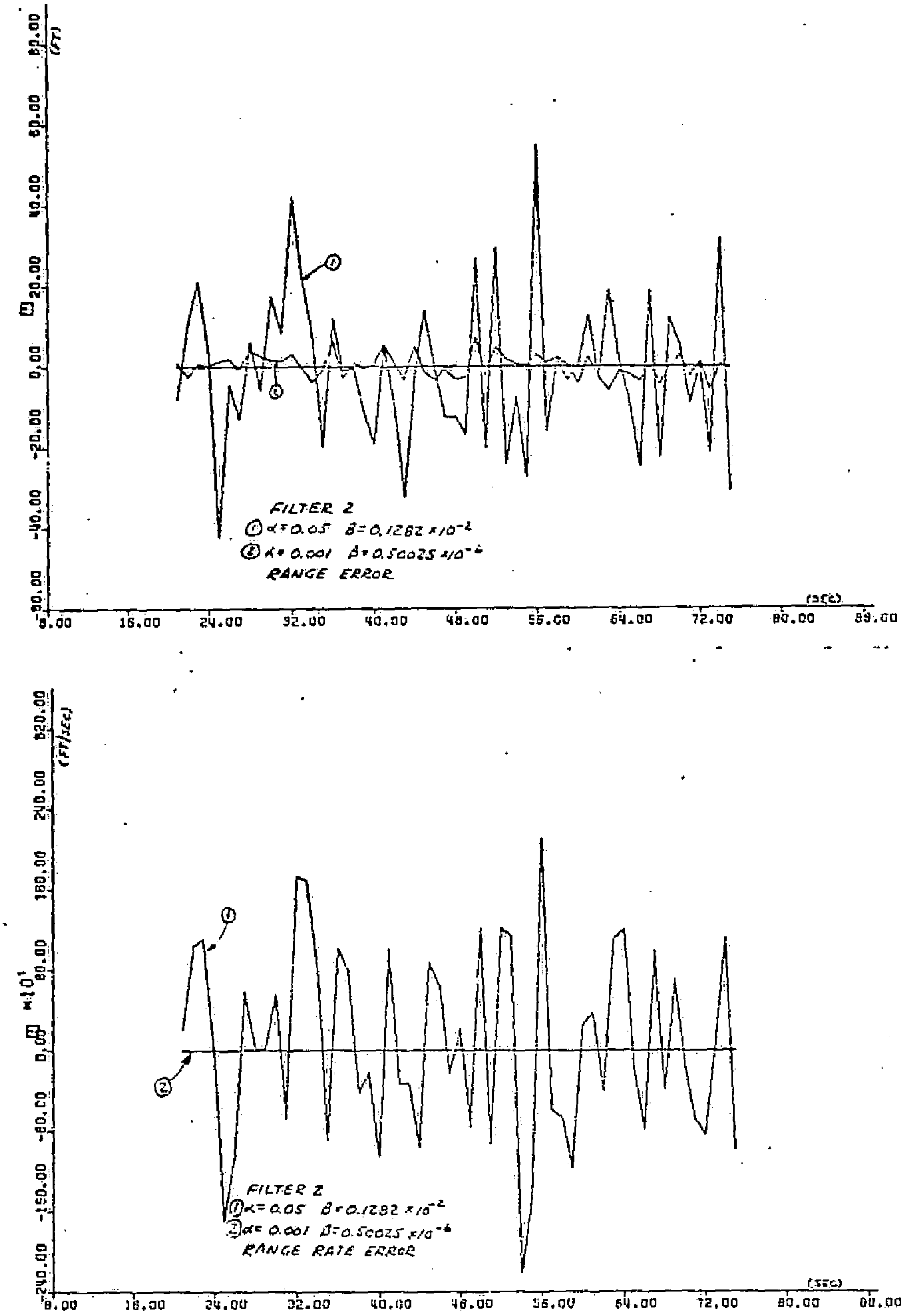


FIGURE 38 - Filter 2 at 2500 samples/sec.

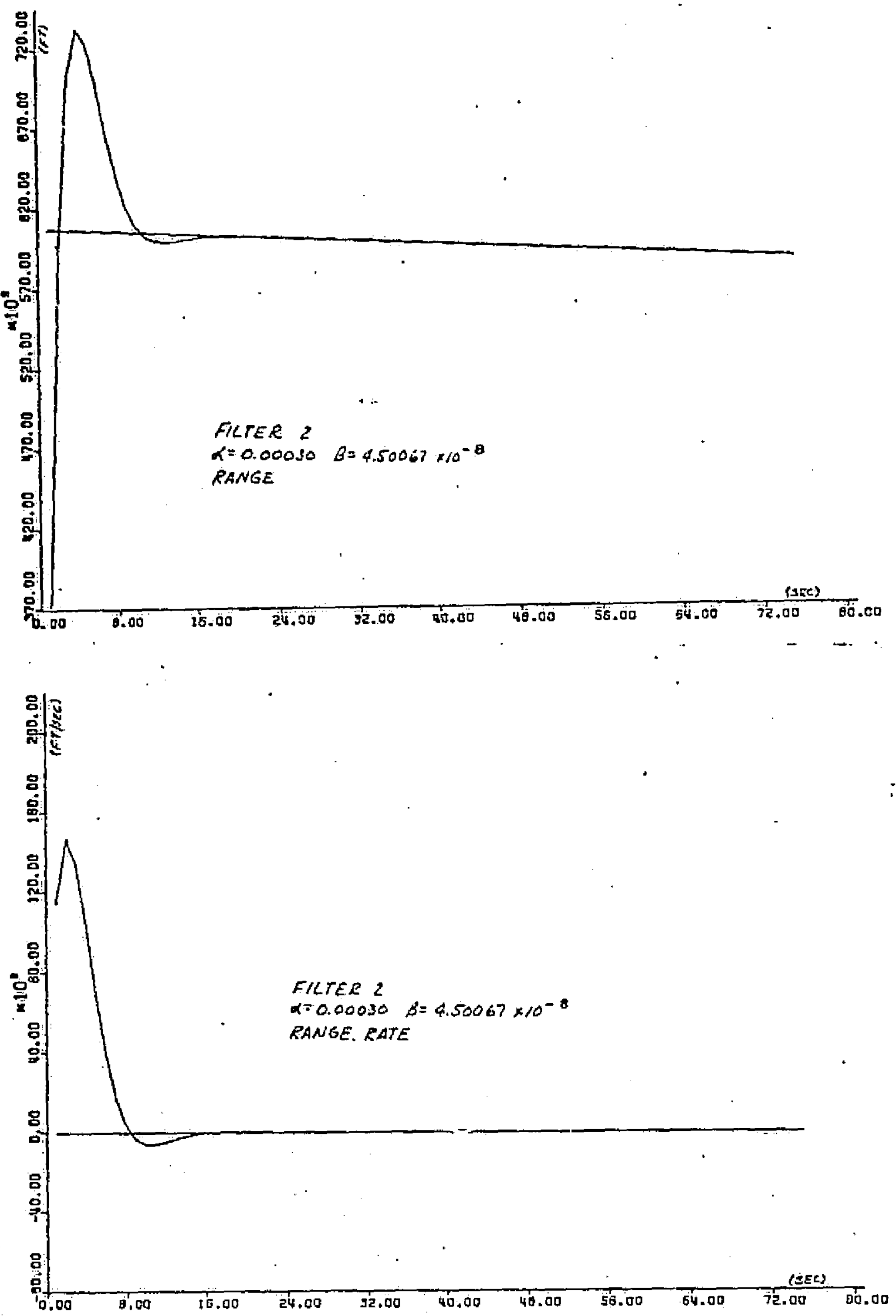


FIGURE 39 - Figure 2 at 2500 samples/sec.

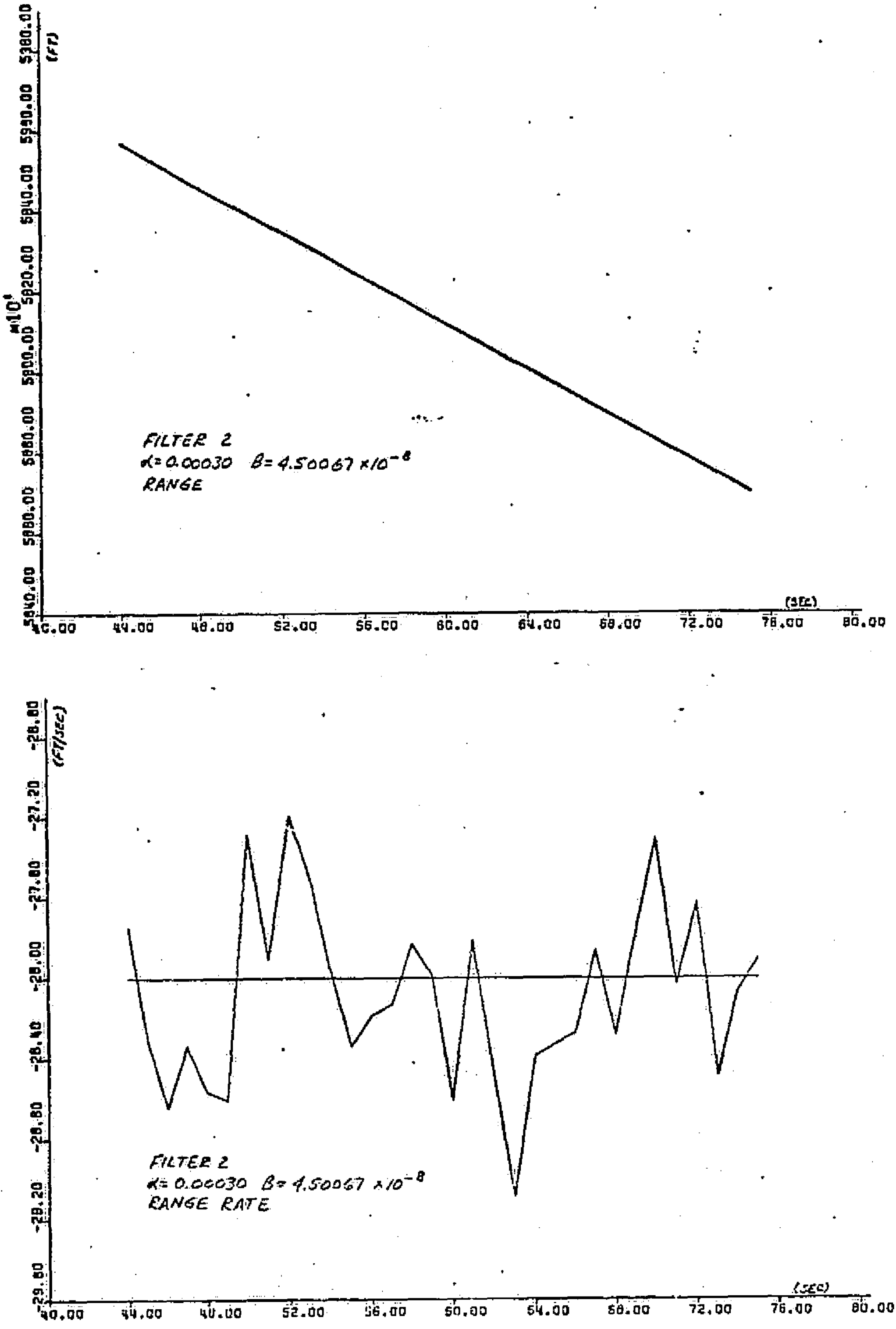


FIGURE 40 - Filter 2 at 2500 samples/sec.

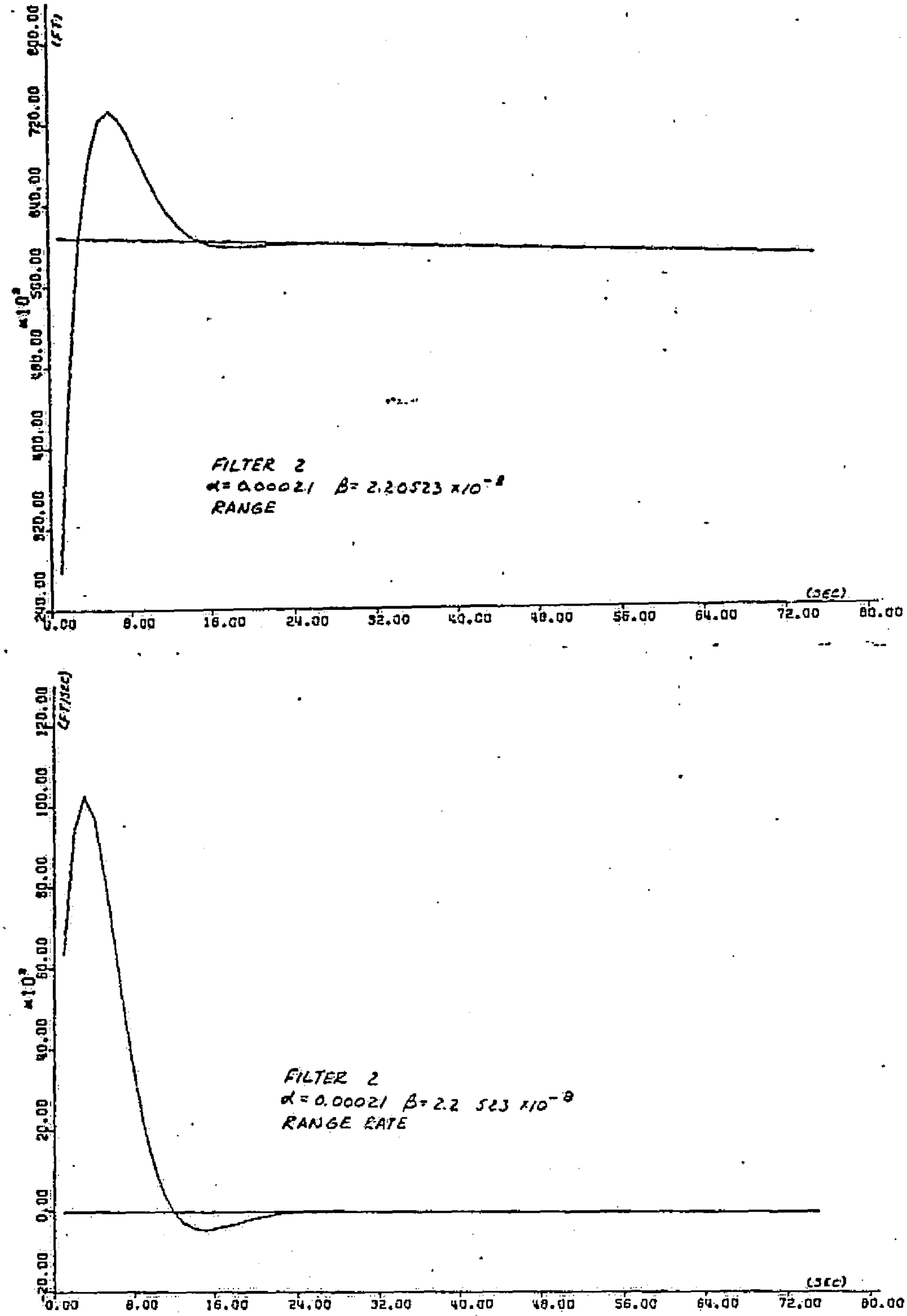


FIGURE 41 - Filter 2 at 2500 samples/sec.

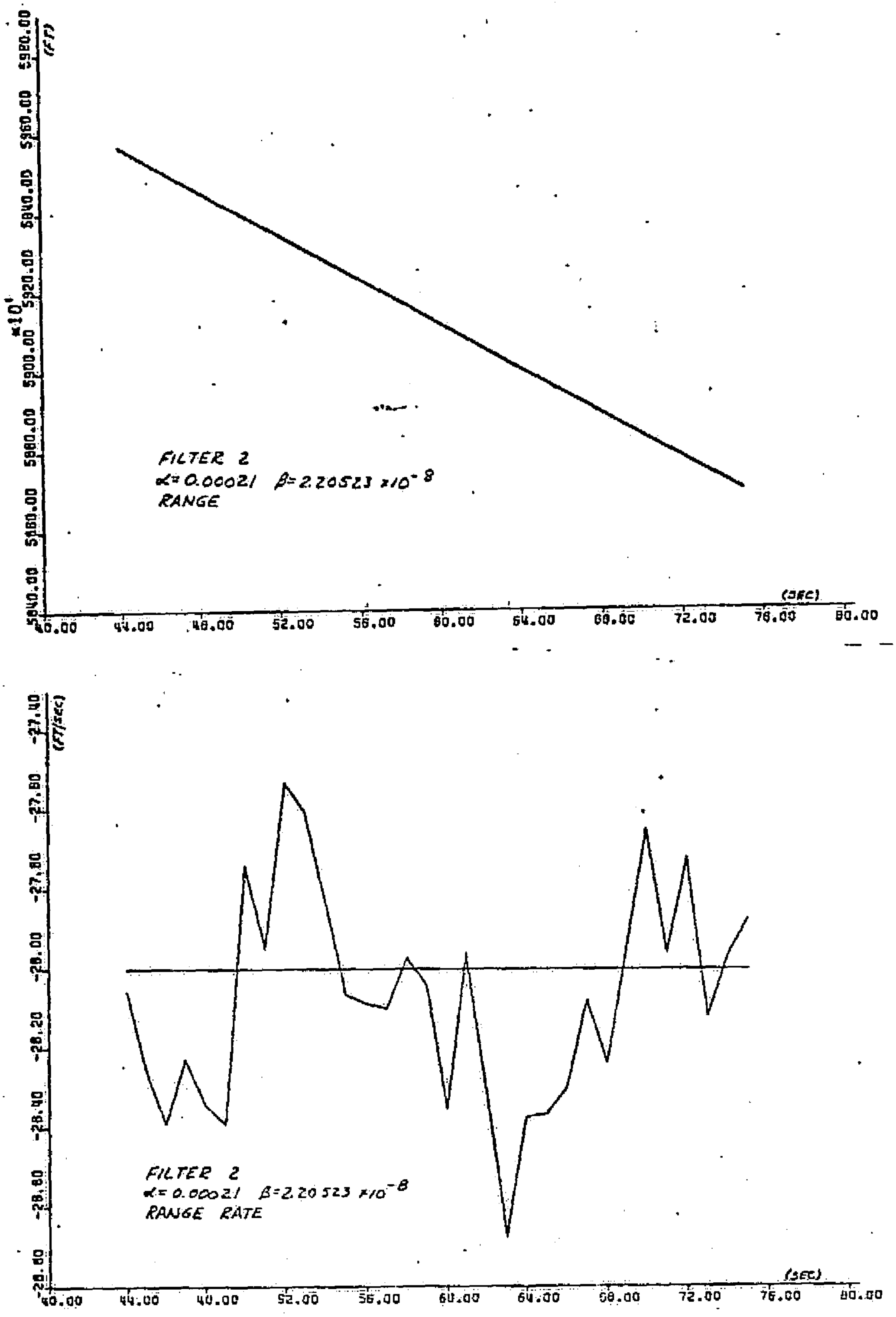


FIGURE 42 - Filter 2 at 2500 samples/sec.

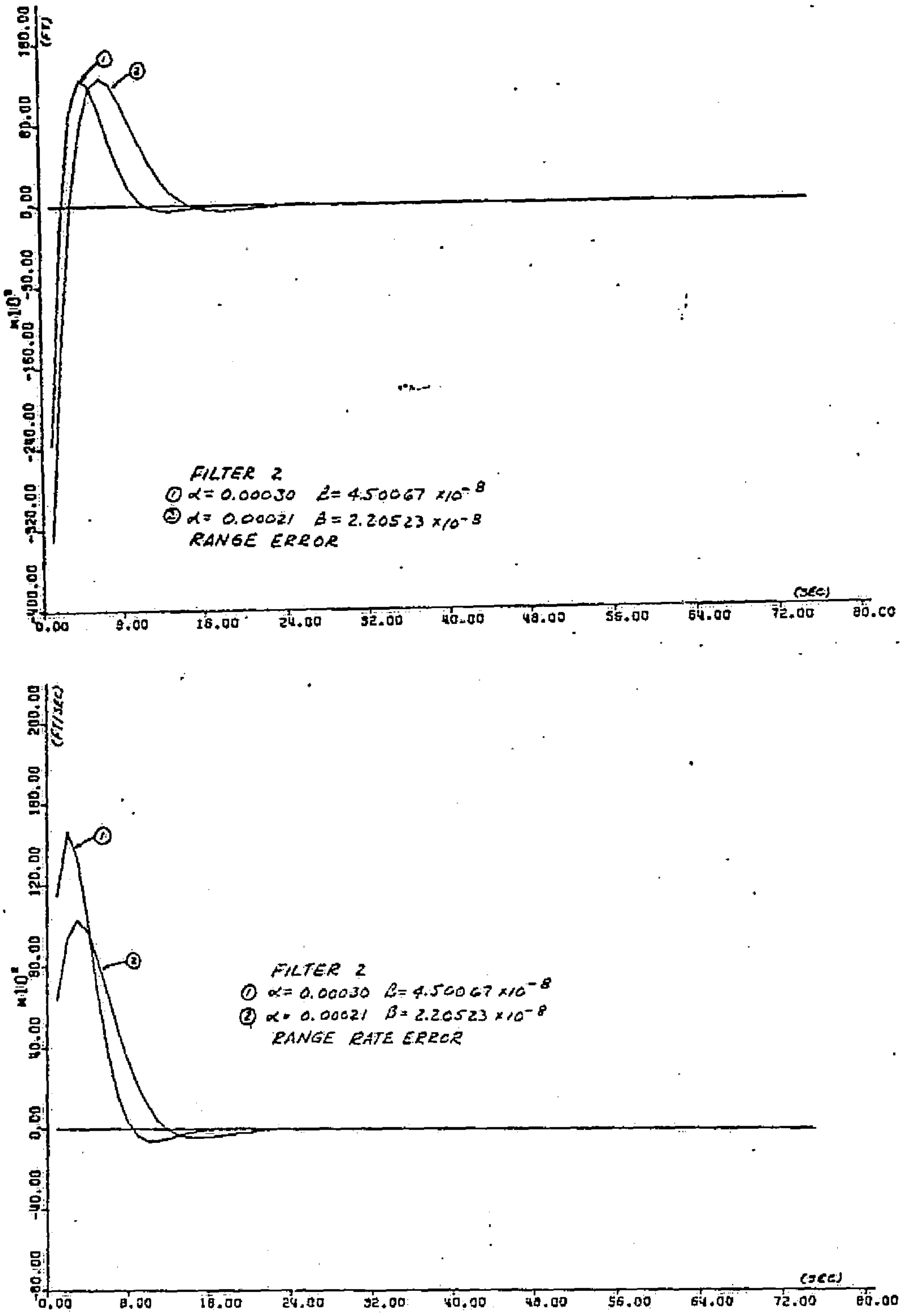


FIGURE 43 - Filter 2 at 2500 samples/sec.

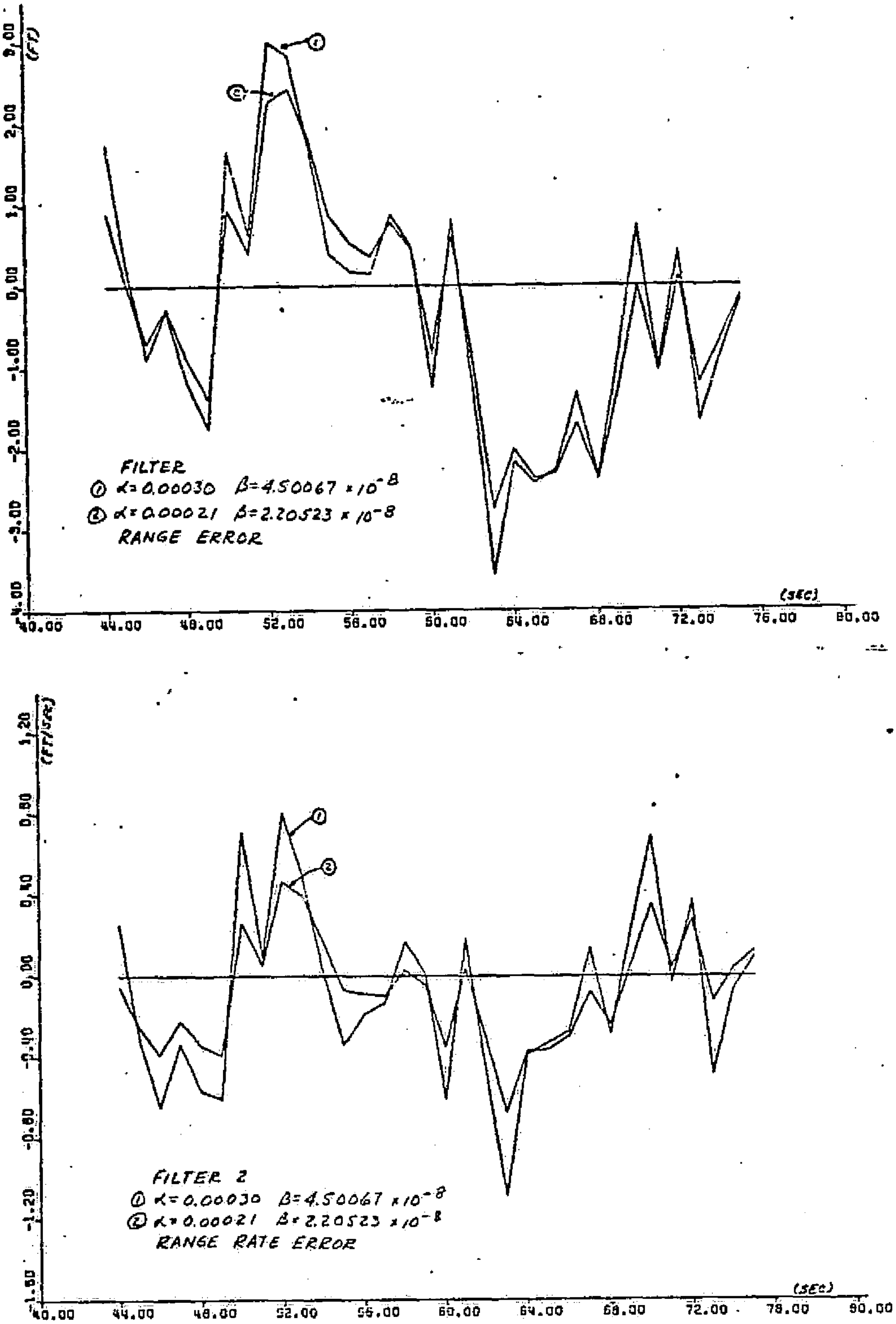


FIGURE 44 - Filter 2 at 2500 samples/sec.

TABLE XXI

FILTER 2 RANGE STANDARD DEVIATIONS(FT.) AT 6.25 SAMPLES /SEC.

	RUN 1 input = ramp		RUN 2 input = noise		RUN 3 input = ramp + noise	
FILTER 2 alpha - beta	INPUT RANGE STND. DEV.	OUTPUT RANGE STND. DEV.	INPUT RANGE STND. DEV.	OUTPUT RANGE STND. DEV.	INPUT RANGE STND. DEV.	OUTPUT RANGE STND. DEV.
$\alpha = 1.0$ $\beta = 1.0$	65.3068	65.3068	91.3215	91.3215	115.2178	115.2178
$\alpha = 0.2$ $\beta = 0.022222$	65.3068	65.3068	91.3215	30.0503	115.2178	83.4223
$\alpha = 0.05$ $\beta = 0.1282 \times 10^{-2}$	65.3068	65.3068	91.3215	8.7326	115.2178	69.3696
$\alpha = 0.001$ $\beta = 5.0025 \times 10^{-7}$	65.3068	—	91.3215	0.2055	115.2178	—
$\alpha = 0.00030$ $\beta = 4.50067 \times 10^{-8}$	65.3068	—	91.3215	0.6791×10^{-1}	115.2178	—
$\alpha = 0.00021$ $\beta = 2.20523 \times 10^{-8}$	65.3068	—	91.3215	0.4817×10^{-1}	115.2178	—

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TABLE XXIII

FILTER 2 MAXIMUM RANGE(FT.) AND RANGE RATE (FT./SEC.) ERRORS AT 6.25 SAMPLES /SEC.

	RUN 1		RUN 2		RUN 3	
	input = ramp		input = noise		input = ramp + noise	
FILTER 2 alpha - beta	MAX RANGE ERROR	MAX RANGE RATE ERROR	MAX RANGE ERROR	MAX RANGE RATE ERROR	MAX RANGE ERROR	MAX RANGE RATE ERROR
$\alpha = 1.0$ $\beta = 1.0$	0.0	0.682×10^{-12}	230.565	1613.121	230.565	1613.121
$\alpha = 0.2$ $\beta = 0.022222$	0.0	0.233×10^{-11}	71.466	51.347	71.466	51.347
$\alpha = 0.05$ $\beta = 0.1282 \times 10^{-2}$	0.646×10^{-8}	0.279×10^{-8}	23.015	3.665	23.015	3.665
$\alpha = 0.001$ $\beta = 5.0025 \times 10^{-7}$	——	——	5.503	0.136×10^{-1}	——	——
$\alpha = 0.00030$ $\beta = 4.50067 \times 10^{-8}$	——	——	1.964	0.172×10^{-2}	——	——
$\alpha = 0.00021$ $\beta = 2.20523 \times 10^{-8}$	——	——	1.404	0.879×10^{-3}	——	——

TABLE XXIV

FILTER 2 RANGE AND RANGE RATE VARIANCE REDUCTION RATIOS AT 6.25 SAMPLES/SEC.

	RUN 2 input = noise		PREDICTED BY BENEDICT AND BORDNER		
FILTER 2 alpha - beta	KR RANGE VARIANCE REDUCTION RATIO	KRR RANGE RATE VARIANCE REDUCTION RATIO	KR	KRR	τ CONVERGENCE TIME (SEC.)
$\alpha = 1.0$ $\beta = 1.0$	1.0	67.778	1.0	78.125	<1
$\alpha = 0.2$ $\beta = 0.022222$	1.083×10^{-1}	4.345×10^{-2}	1.554×10^{-1}	5.392×10^{-2}	15
$\alpha = 0.05$ $\beta = 0.1282 \times 10^{-2}$	9.144×10^{-3}	2.842×10^{-4}	3.782×10^{-2}	6.587×10^{-4}	56
$\alpha = 0.001$ $\beta = 5.0025 \times 10^{-7}$	5.064×10^{-6}	4.160×10^{-11}	7.501×10^{-4}	4.890×10^{-9}	>192
$\alpha = 0.00030$ $\beta = 4.50067 \times 10^{-8}$	5.530×10^{-7}	4.497×10^{-13}	2.250×10^{-4}	1.319×10^{-10}	>192
$\alpha = 0.00021$ $\beta = 2.20523 \times 10^{-8}$	2.782×10^{-7}	1.132×10^{-13}	1.575×10^{-4}	4.523×10^{-11}	>192

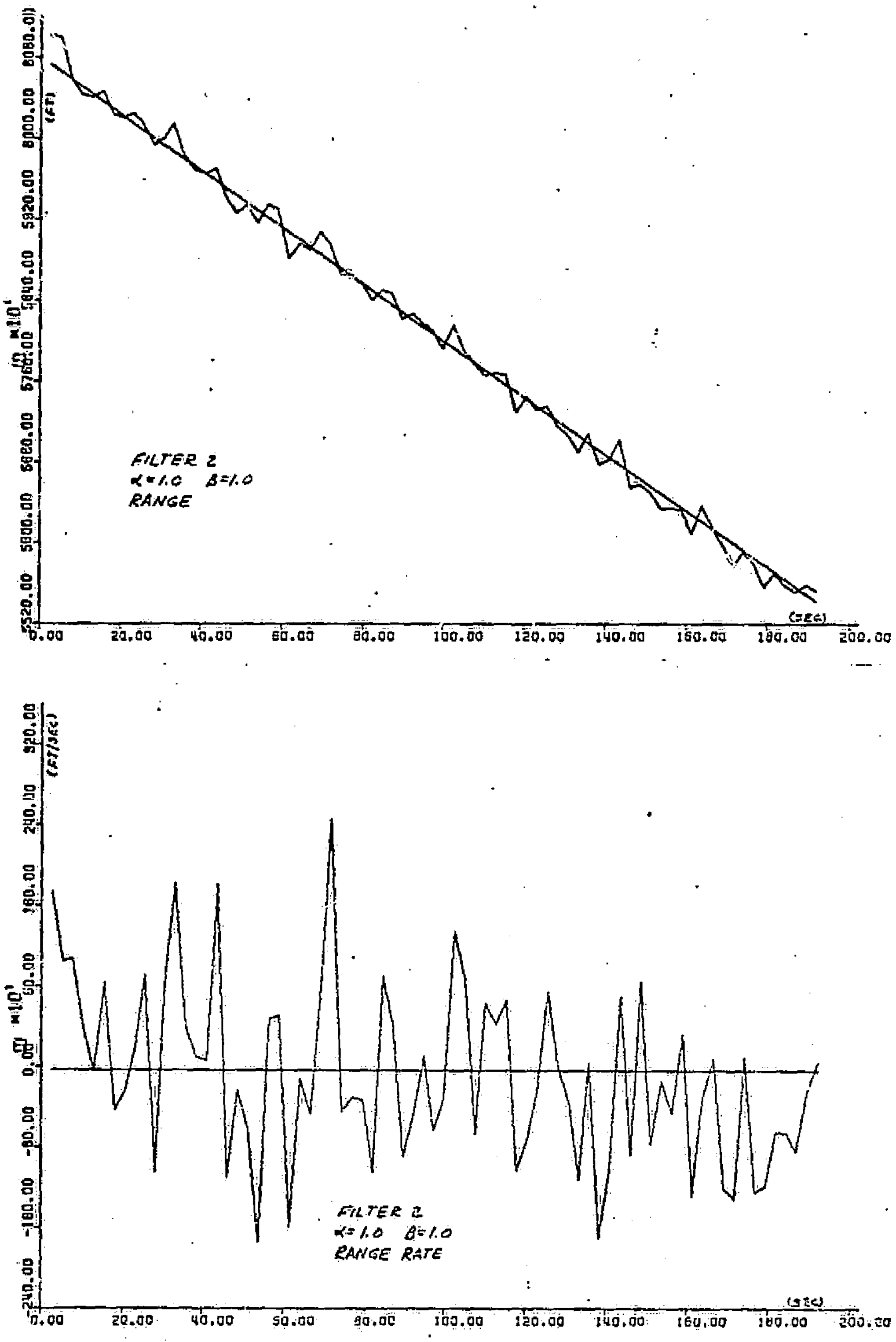


FIGURE 45 - Filter 2 at 6.25 samples/sec.

C2

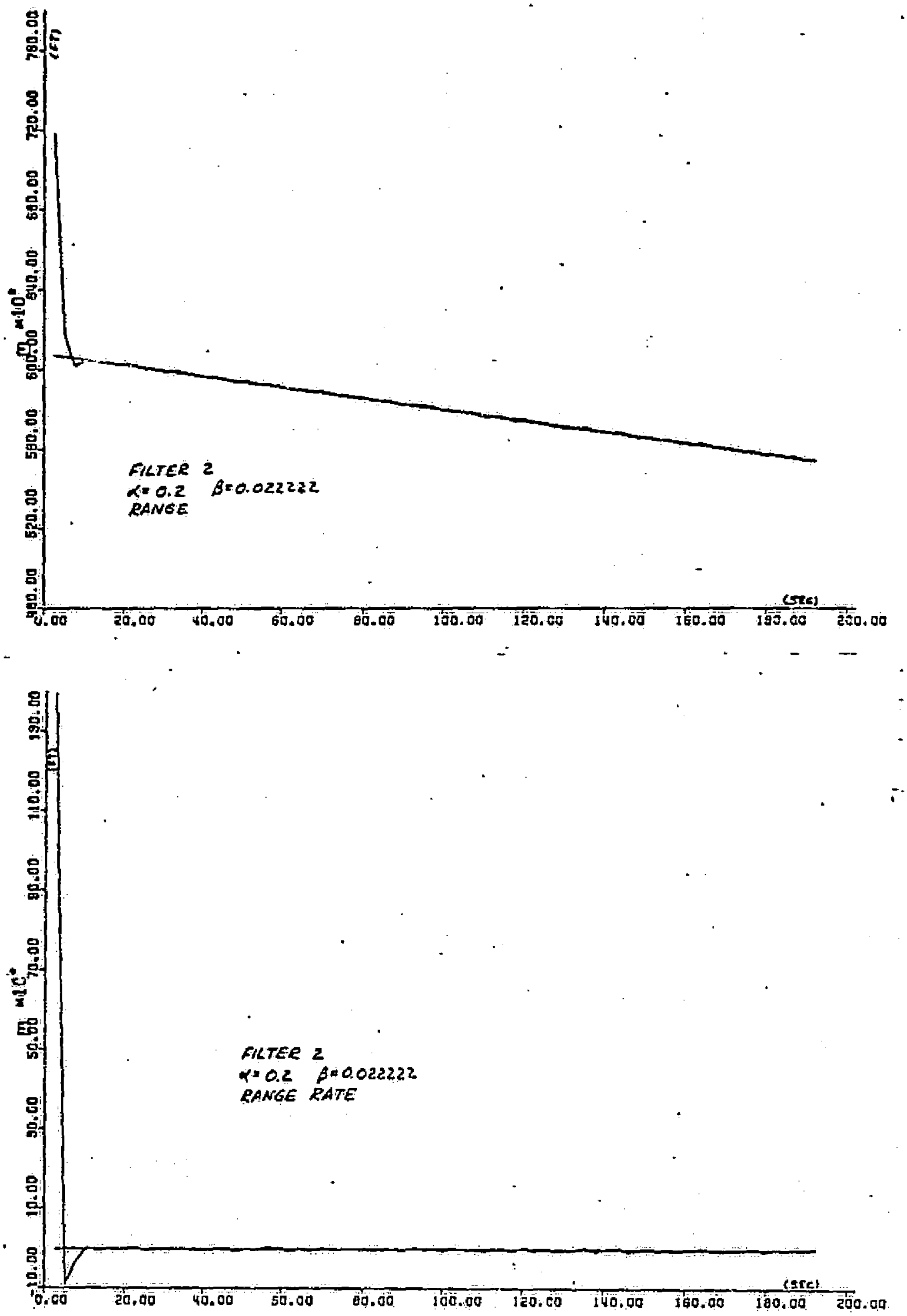
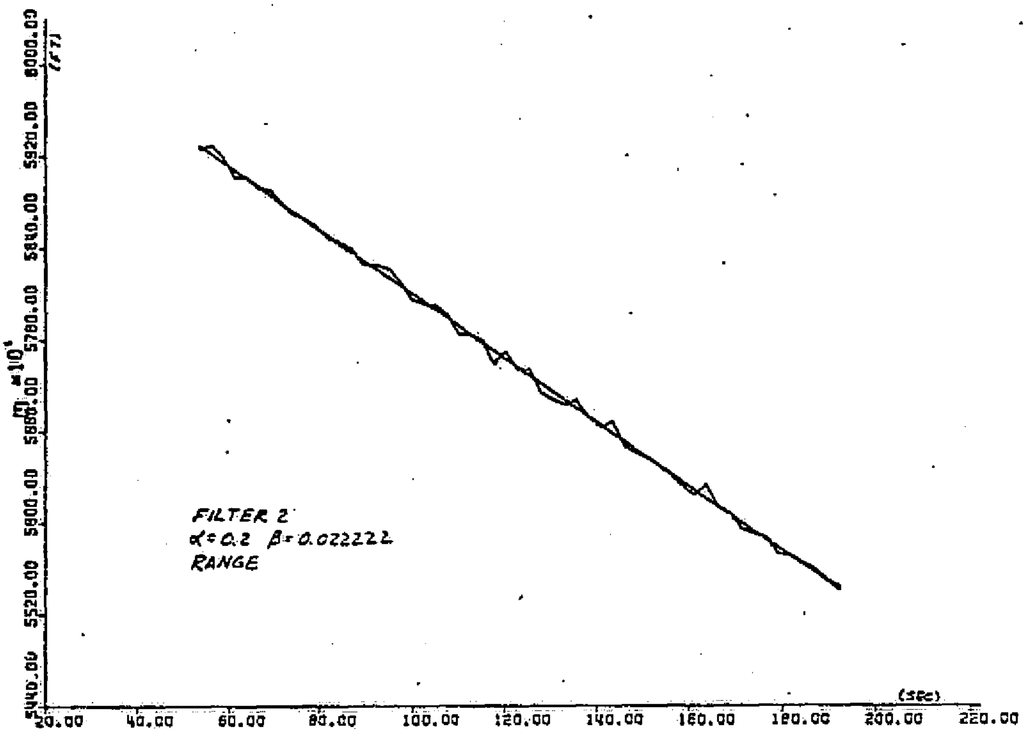


FIGURE 46 - Filter 2 at 6.25 samples/sc·.



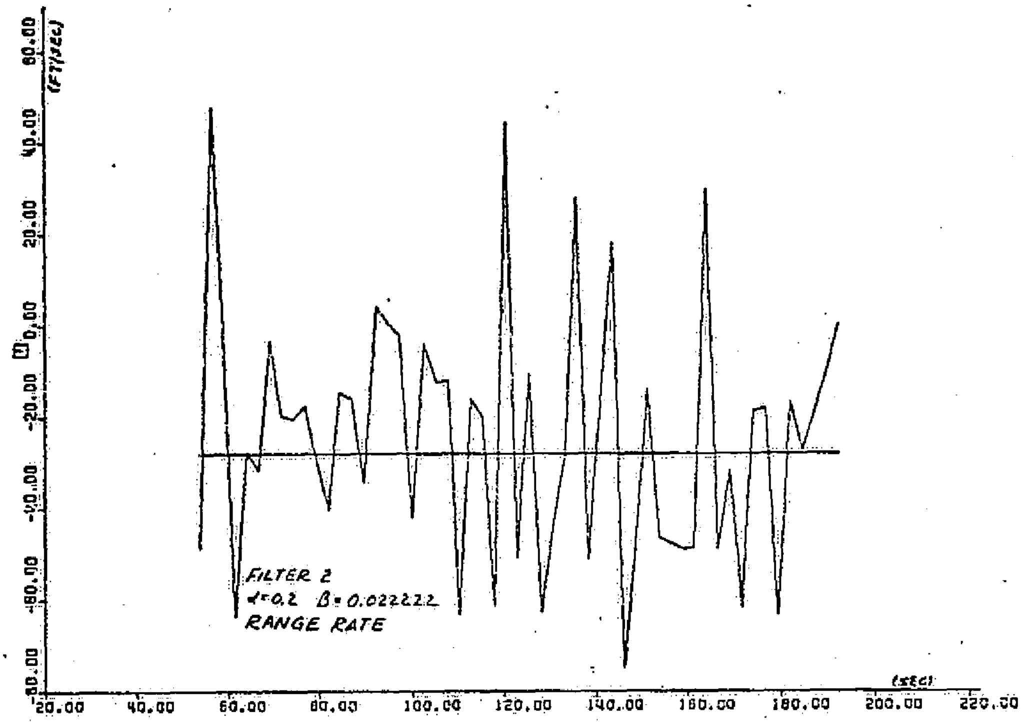


FIGURE 47 - Filter 2 at 6.25 samples/sec.

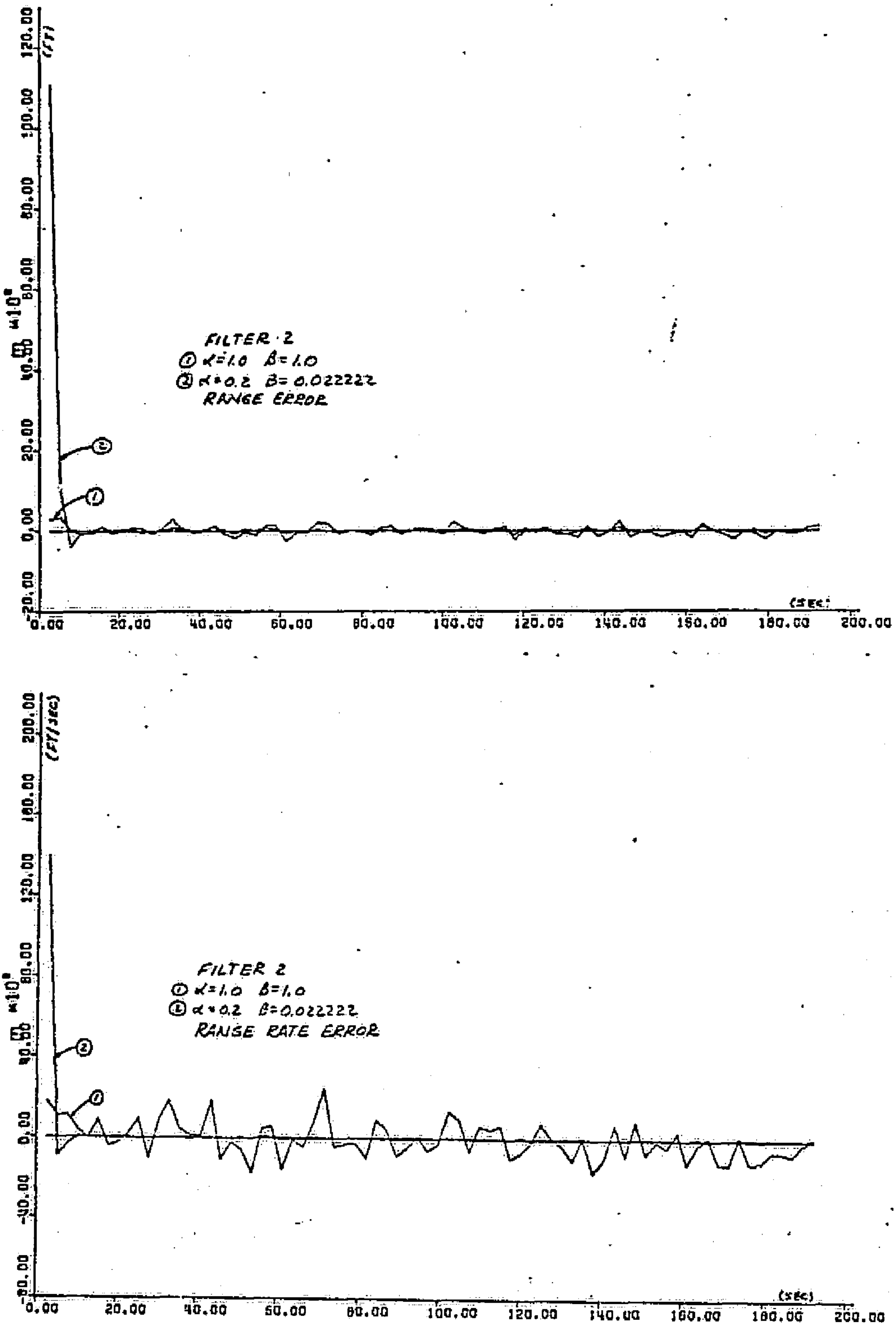


FIGURE 48 - Filter 2 at 6.25 samples/sec.

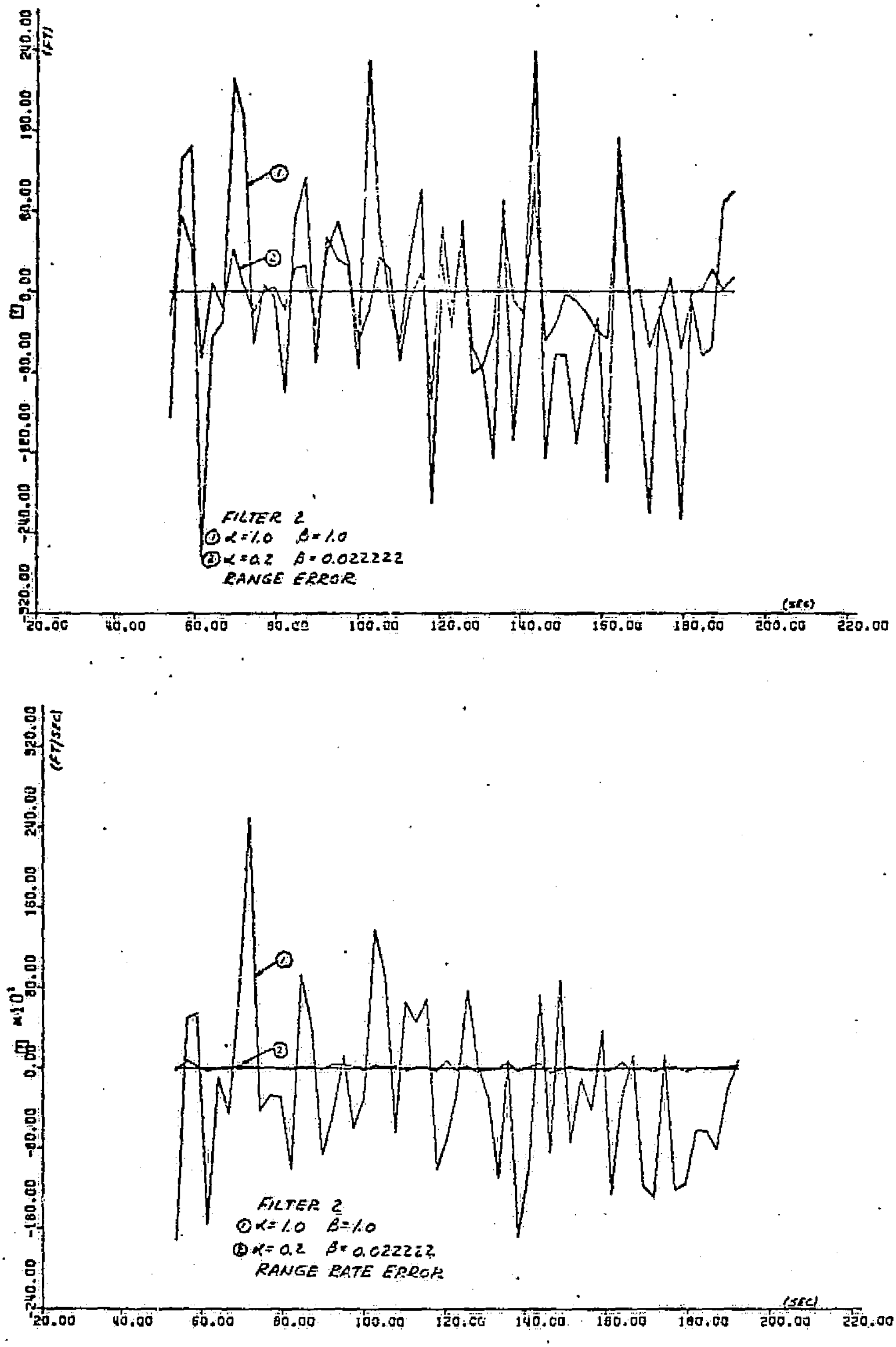


FIGURE 49 - Filter 2 at 6.25 samples/sec.

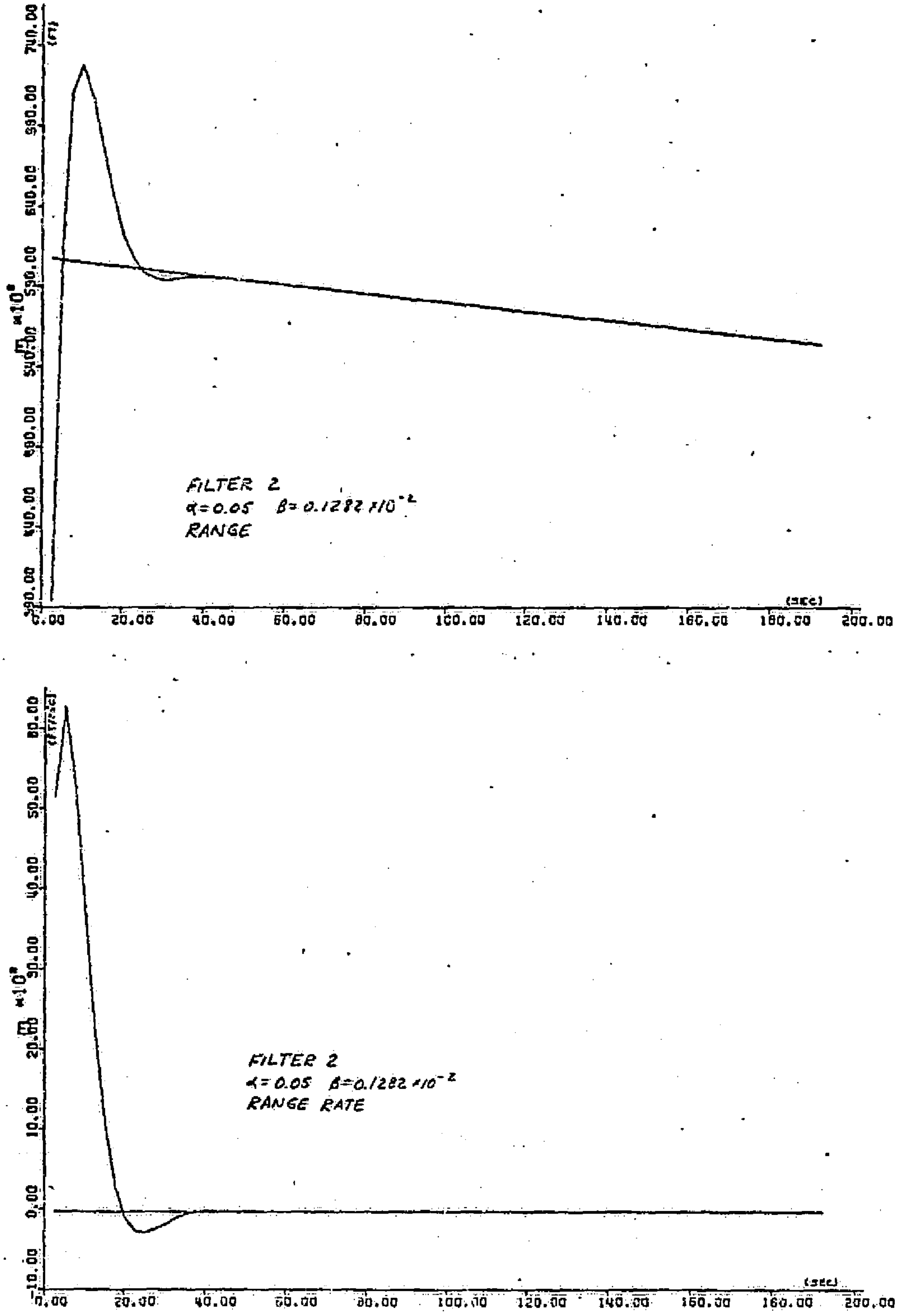
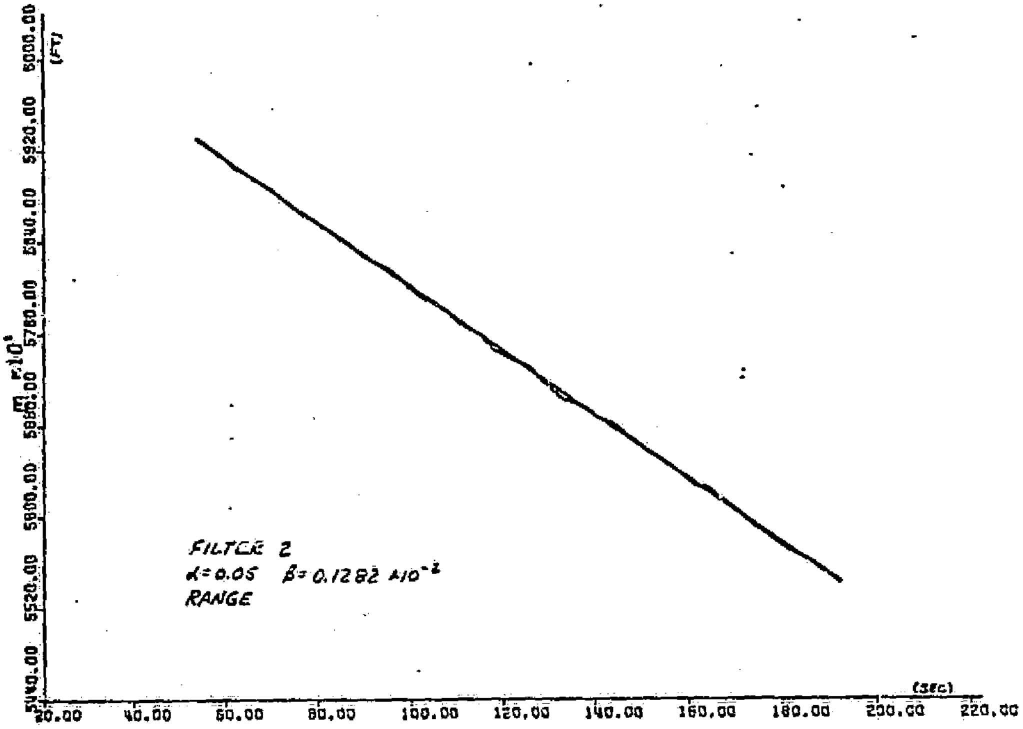


FIGURE 50 - Filter 2 at 6.25 samples/sec.



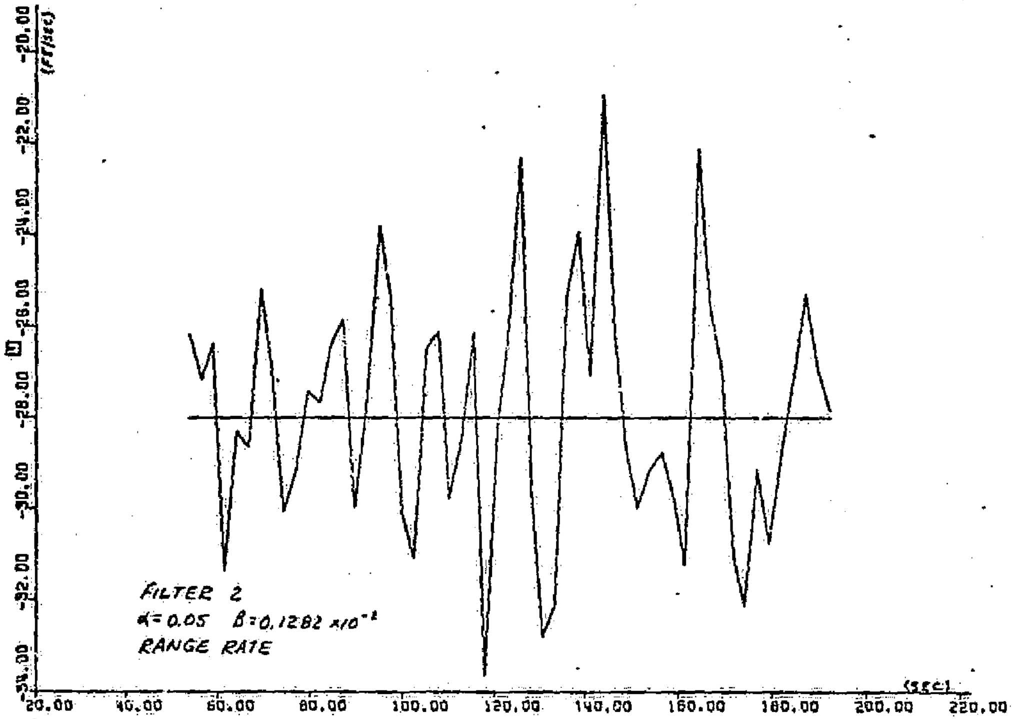


FIGURE 51 - Filter 2 at 6.25 samples/sec.

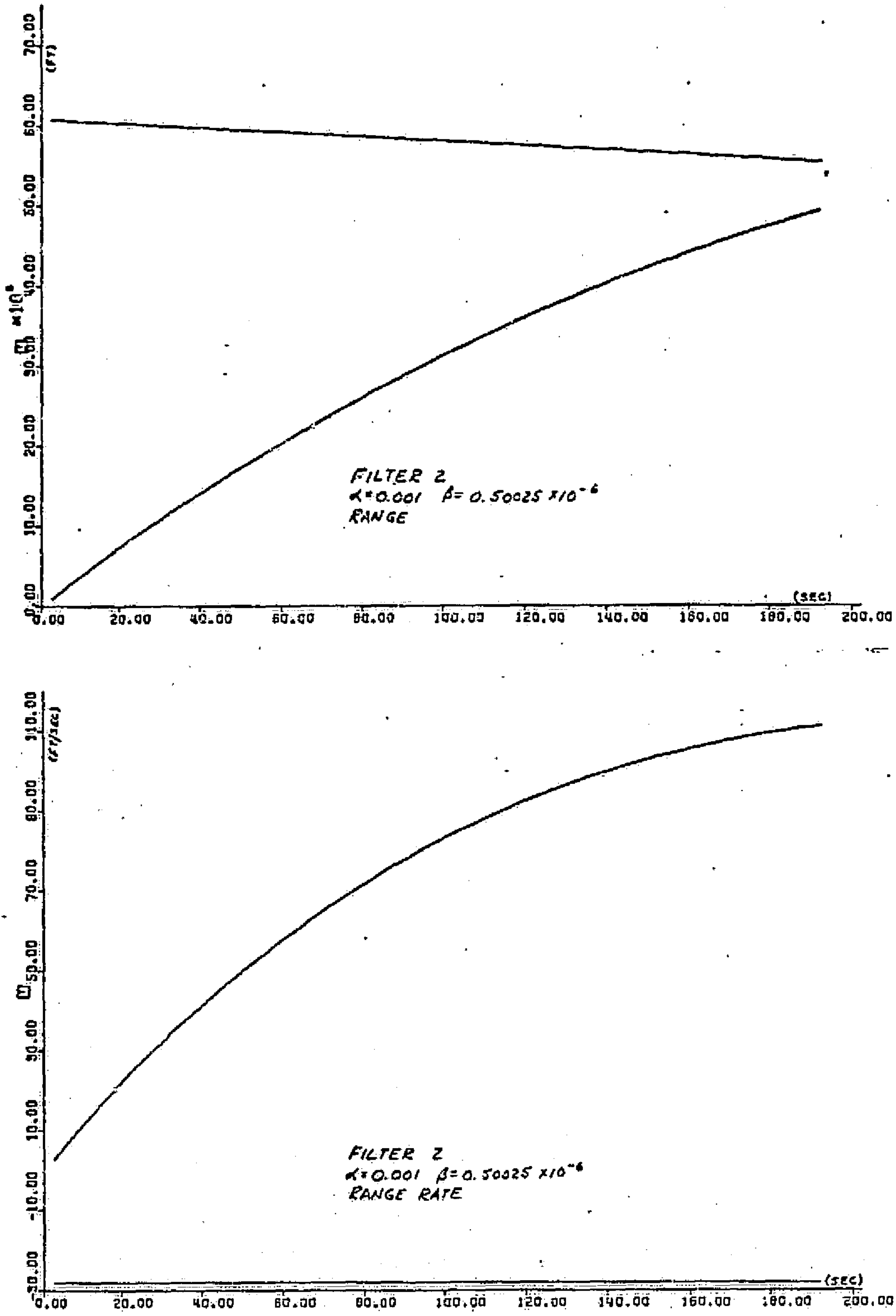


FIGURE 52 - Filter 2 at 6.25 samples/sec.

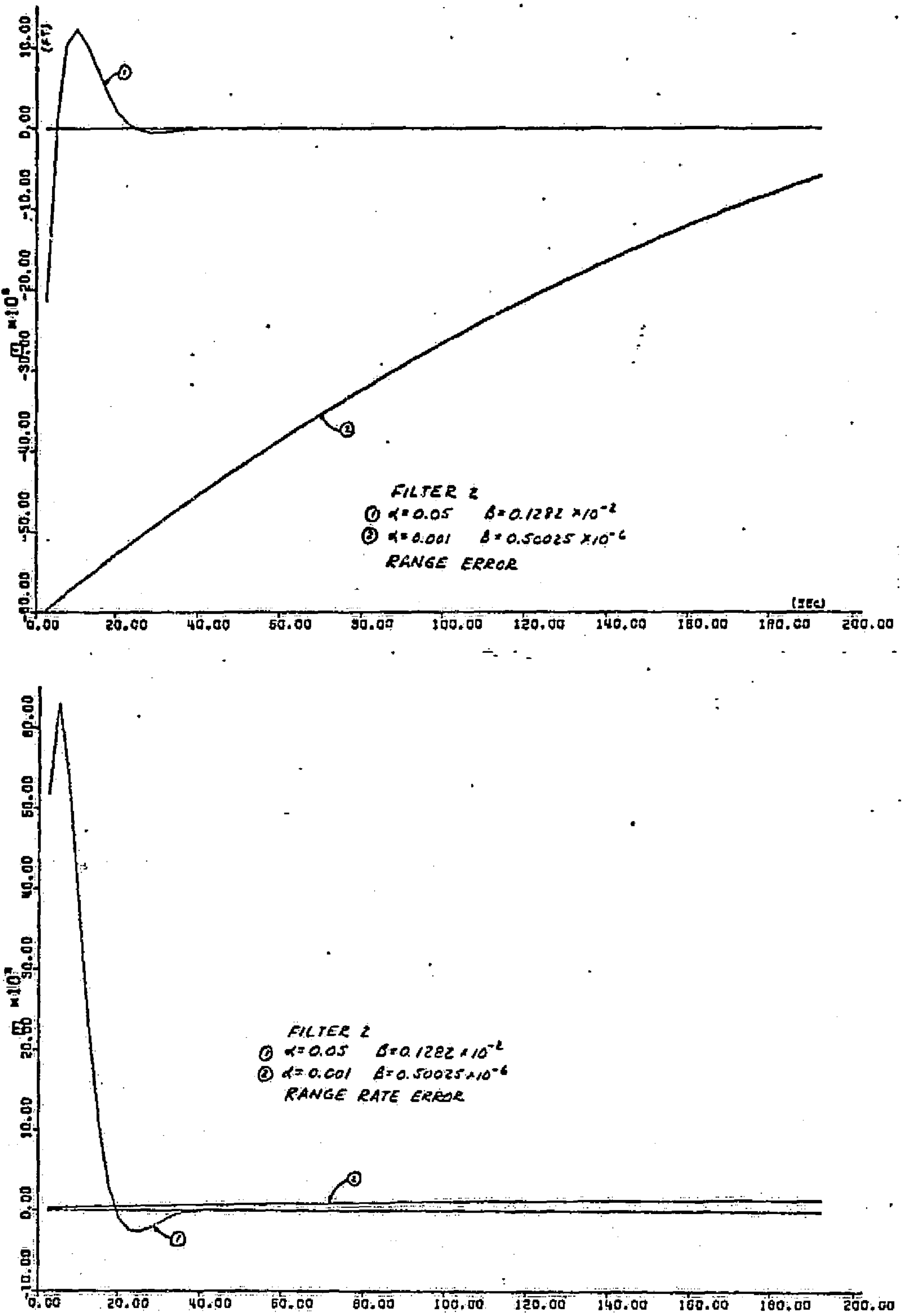


FIGURE 53 - Filter 2 at 6.25 samples/sec.

second duration of the tests. For this reason steady state values for output range and range rate standard deviations are not given.

The range variance reduction ratio is not a function of sampling rate as can be seen by comparing that value for both rates. The range rate variance reduction ratio, however, is proportional to the square of the sampling rate and demonstrates a decrease with a reduction of sampling rate.

Overall, data from the simulation runs for the alpha-beta filter agrees with the variance reduction ratios predicted by Benedict and Bordner.[5] Deviations become apparent as alpha and especially beta decrease in magnitude.

3. Filter 3

Simulation data for Filter 3 is presented in Tables XXV - XXVIII for 2500 samples/second and Tables XXIX - XXXII for the 6.25 samples/second sampling rate. A graphical display of this data is shown in Figures 54 and 55 for 2500 samples/second and Figures 56 and 57 for 6.25 samples/second.

The N sample smoother employed to derive range in Filter 3 smooths over sixteen samples. That is a sufficient number of samples to provide good filtering. However, its performance is not readily apparent from the data. Since the smoother provides a range value that lags the present sample instant by 7.5 sampling periods, updating is necessary. To accomplish this a correction term is determined from the estimated range rate calculated for that sample instant. This updating introduces error into the estimated range.

For simulation RUN 2, since both the range and range rate segments of Filter 3 are linear systems and the input is a random signal, the estimated range before correction for the 7.5 sample period lag (RE lagging) and the estimated range rate (RDOT) are random signals. The operation of correction for lag can then be described in terms of variances as

$$\sigma^2_{\text{RE lagging}} + (K\,\sigma_{\text{RDOT}})^2 = \sigma^2_{\text{RE}} \tag{22}$$

where K is the constant 7.5 * DT. Using the values for estimated range standard deviation (σ_{RE}) and estimated range rate standard deviation (σ_{RDOT}) listed under RUN 2 in the tables for Filter 3, the standard deviation of the lagging estimated range ($\sigma_{\text{RE lagging}}$) can be obtained. This value is 3.9291m.(12.8908 ft.) and 7.0905m.(23.2627 ft.) for the 2500 and 6.25 samples/second simulations, respectively. The associated range variance reduction ratios are

$$KR_{2500} = \left(\frac{12.8908}{110.7364}\right)^2 = 1.355 \times 10^{-2} \tag{23}$$

$$KR_{6.25} = \left(\frac{23.2627}{91.3215}\right)^2 = 6.489 \times 10^{-2} \tag{24}$$

This is in agreement with the $\frac{1}{N}$ variance reduction ratio of an N sample smoother. A comparison can be made of these ratios to those given in the tables to demonstrate the effect the updating procedure has on noise rejection in range determination.

TABLE XXV

FILTER 3 RANGE STANDARD DEVIATIONS(FT.) AT 2500 SAMPLES/SEC.

	RUN 1 input = ramp		RUN 2 input = noise		RUN 3 input = ramp + noise	
	INPUT RANGE STND. DEV.	OUTPUT RANGE STND. DEV.	INPUT RANGE STND. DEV.	OUTPUT RANGE STND. DEV.	INPUT RANGE STND. DEV.	OUTPUT RANGE STND. DEV.
FILTER 3	0.1634	0.1634	110.7364	34.7179	110.7339	34.6758

TABLE XXVI

FILTER 3 RANGE RATE STANDARD DEVIATIONS(FT./SEC.) AT 2500 SAMPLES/SEC.

	RUN 1 OUTPUT RANGE RATE STND. DEV.	RUN 2 OUTPUT RANGE RATE STND. DEV.	RUN 3 OUTPUT RANGE RATE STND. DEV.
FILTER 3	0.0	10745.3359	10745.3359

TABLE XXVII

FILTER 3 MAXIMUM RANGE(FT.) AND RANGE RATE(FT./SEC.) ERRORS AT 2500 SAMPLES/SEC.

	RUN 1 input = ramp		RUN 2 input = noise		RUN 3 input = ramp + noise	
	MAX RANGE ERROR	MAX RANGE RATE ERROR	MAX RANGE ERROR	MAX RANGE RATE ERROR	MAX RANGE ERROR	MAX RANGE RATE ERROR
FILTER 3	0.364×10^{-11}	0.207×10^{-8}	114.486	28399.3	114.4859	28399.3

TABLE XXVIII

FILTER 3 RANGE AND RANGE RATE VARIANCE REDUCTION RATIOS AT 2500 SAMPLES/SEC.

	RUN 2		
	KR range variance reduction ratio	KRR range rate variance reduction ratio	τ Convergence Time (Sec.)
FILTER 3	9.829×10^{-2}	9.416×10^{3}	<1

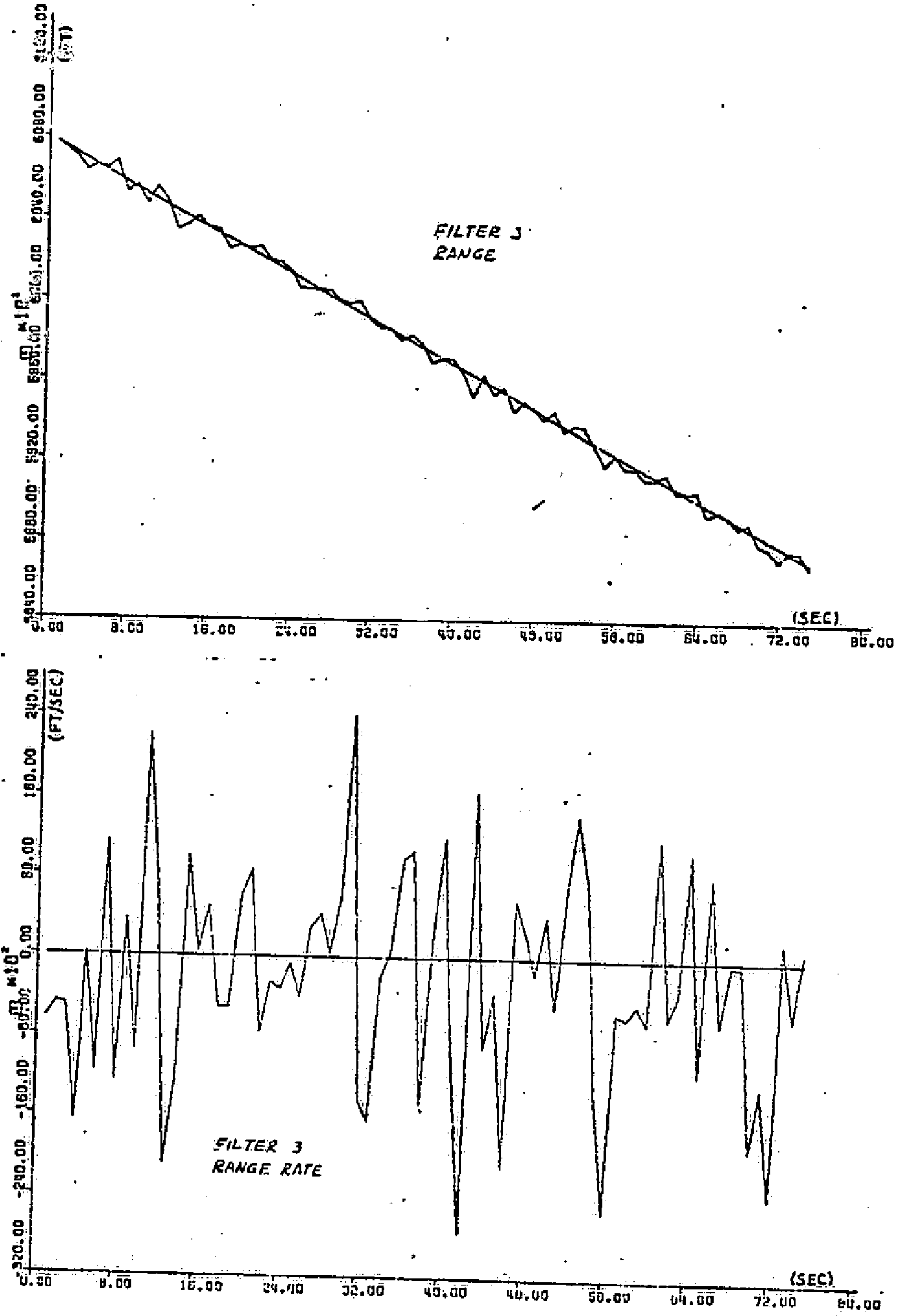


FIGURE 54 - Filter 3 at 2500 samples/sec.

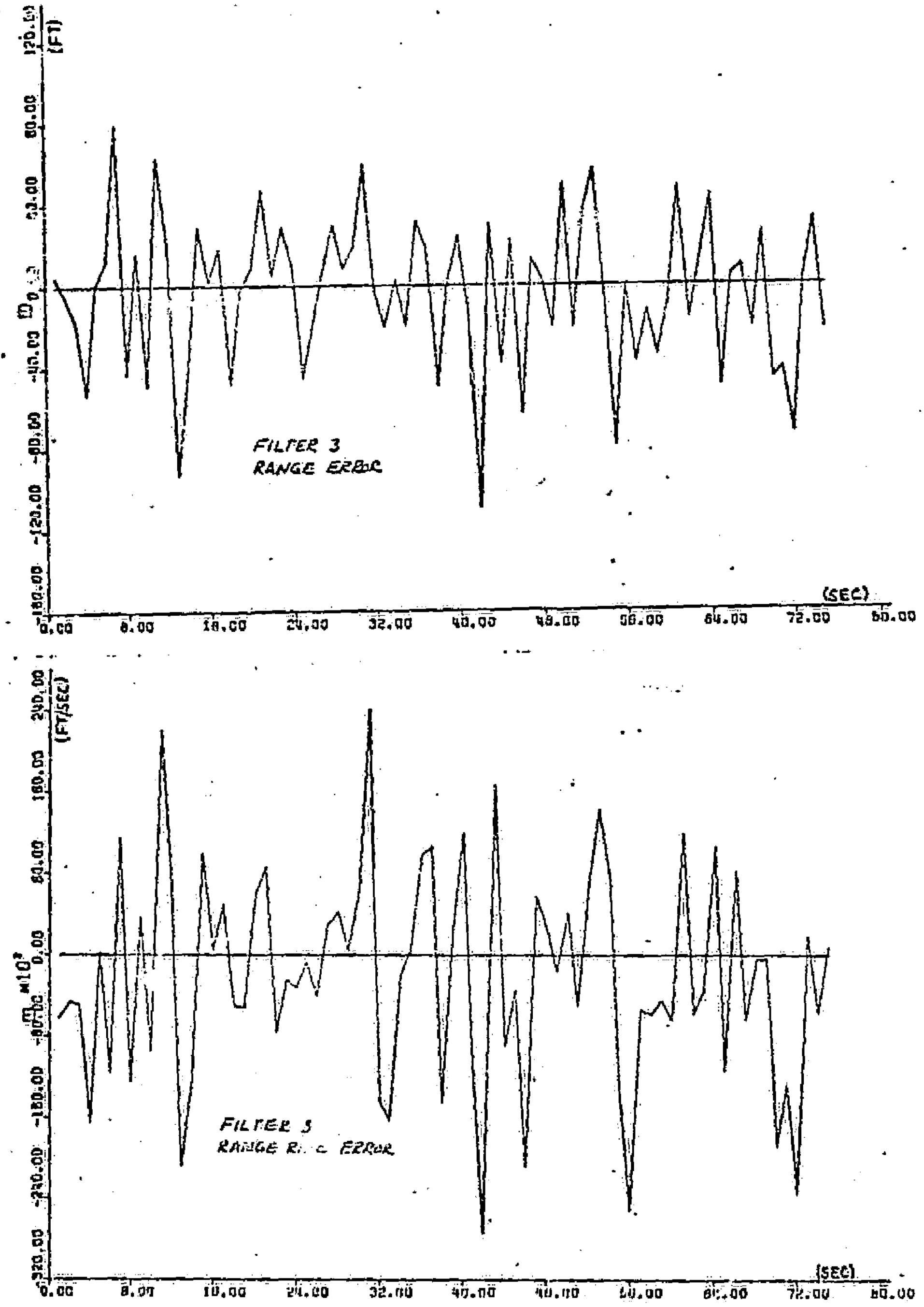


FIGURE 55 - Filter 3 at 2500 samples/sec.

TABLE XXIX

FILTER 3 RANGE STANDARD DEVIATIONS(FT.) AT 6.25 SAMPLES/SEC.

	RUN 1 input = ramp		RUN 2 input = noise		RUN 3 input = ramp + noise	
	INPUT RANGE STND. DEV.	OUTPUT RANGE STND. DEV.	INPUT RANGE STND. DEV.	OUTPUT RANGE STND. DEV.	INPUT RANGE STND. DEV.	OUTPUT RANGE STND. DEV.
FILTER 3	65.3068	65.3068	91.3215	36.3516	115.2178	86.9980

TABLE XXX

FILTER 3 RANGE RATE STANDARD DEVIATIONS(FT./SEC.) AT 6.25 SAMPLES/SEC.

	RUN 1 OUTPUT RANGE RATE STND. DEV.	RUN 2 OUTPUT RANGE RATE STND. DEV.	RUN 3 OUTPUT RANGE RATE STND. DEV.
FILTER 3	0.0	23.2780	23.2780

TABLE XXXI

FILTER 3 MAXIMUM RANGE(FT.) AND RANGE RATE(FT./SEC.) ERRORS AT 6.25 SAMPLES/SEC.

	RUN 1 input = ramp		RUN 2 input = noise		RUN 3 input = ramp + noise	
	MAX RANGE ERROR	MAX RANGE RATE ERROR	MAX RANGE ERROR	MAX RANGE RATE ERROR	MAX RANGE ERROR	MAX RANGE RATE ERROR
FILTER 3	0.727×10^{-11}	0.296×10^{-11}	104.0342	65.5469	104.0342	65.5469

TABLE XXXII

FILTER 3 RANGE AND RANGE RATE VARIANCE REDUCTION RATIOS AT 6.25 SAMPLES/SEC.

	RUN 2		
	KR range variance reduction ratio	KRR range rate variance reduction ratio	τ Convergence Time (Sec.)
FILTER 3	1.584×10^{-1}	6.497×10^{-2}	.3

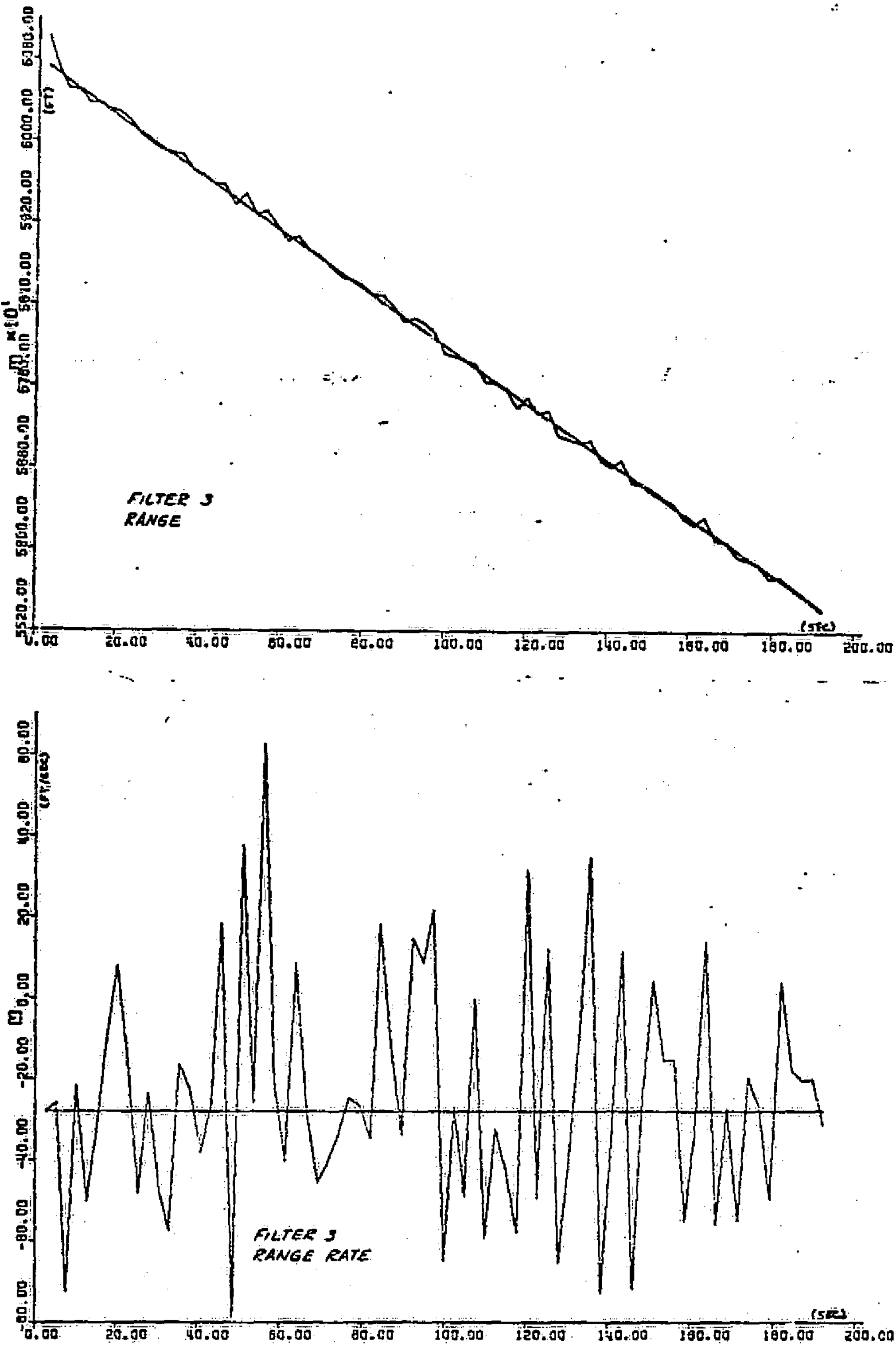


FIGURE 56 - Filter 3 at 6.25 samples/sec.

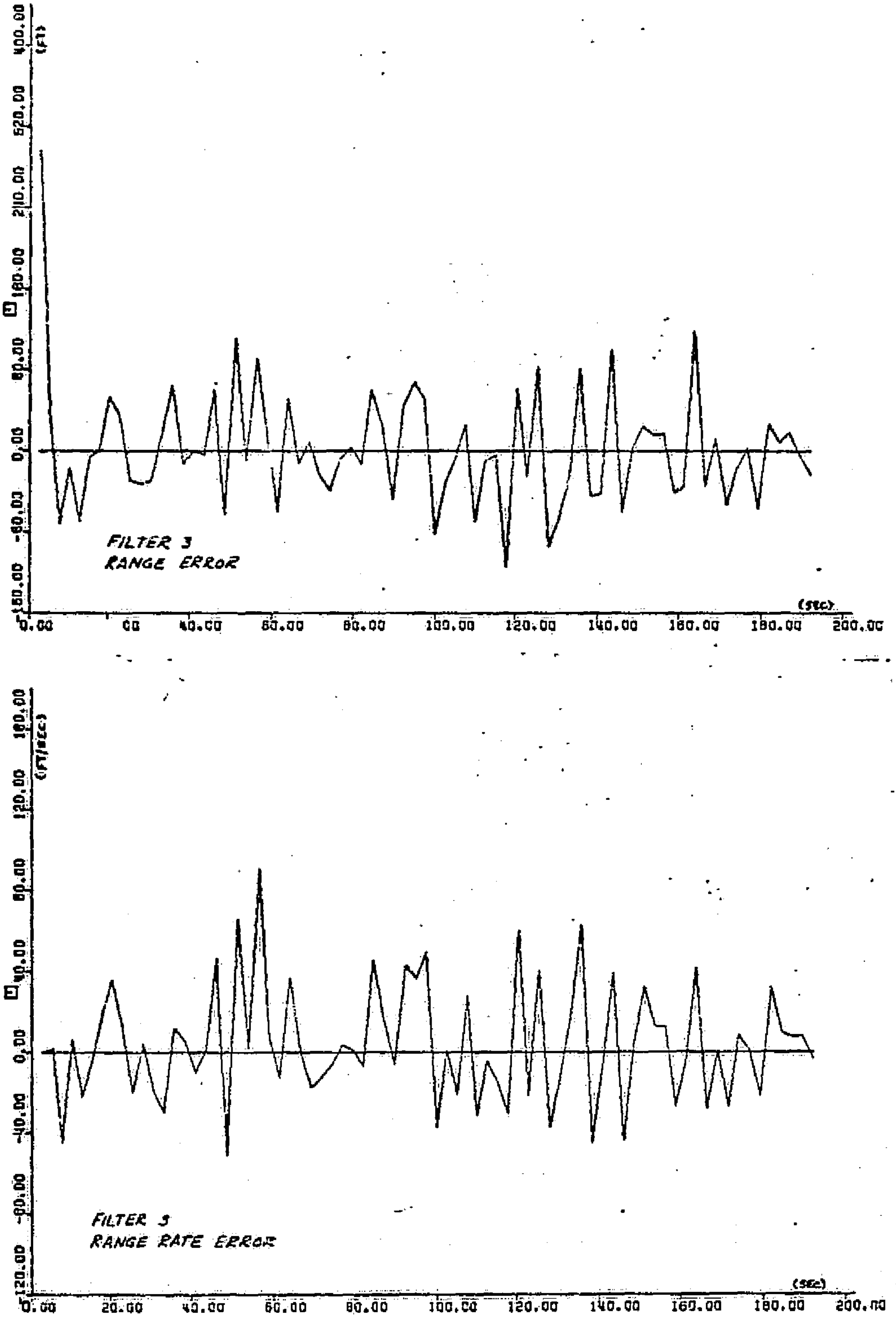


FIGURE 57 - Filter 3 at 6.25 samples/sec.

The range rate determining section of Filter 3 is a cascaded simple average smoother. The range rate variance reduction ratio is given by[6]

$$\frac{\sigma^2_{\text{RANGE RATE OUTPUT}}}{\sigma^2_{\text{RANGE INPUT}}} = \frac{2\ n_2}{(n_1 n_2\ DT)^2}\ , \qquad (25)$$

where n_1 is the number of samples over which the first differences are taken ($n_1 = 12$) and n_2 is the number of first differences that are smoothed ($n_2 = 6$). Simulation runs at both 2500 and 6.25 samples/second support the above relation. Operation at 6.25 samples/second gives improved results due to the dependence of the variance reduction ratio on the square of the sampling period DT.

4. Filter 4

Simulation data for Filter 4 is presented in Tables XXXIII - XXXVI for 2500 samples/second and in Tables XXXVII - XL for 6.25 samples/second. A graphical display of this data is shown in Figures 58 and 59 for 2500 samples/second and in Figure 60 and 61 for 6.25 samples/second.

The digital tracking filter smoothing over four samples has the transfer functions

$$H_R = \frac{RE}{RM} = \frac{1 + z^{-1} + z^{-2} + z^{-3}}{1 - 0.75\ z^{-1} + 0.25z^{-2} + 0.25z^{-3} + 0.25z^{-4}} \qquad (26)$$

and

TABLE XXXIII

FILTER 4 RANGE STANDARD DEVIATIONS(FT.) AT 2500 SAMPLES/SEC.

	RUN 1 input = ramp		RUN 2 input = noise		RUN 3 input = ramp + noise	
	INPUT RANGE STND. DEV.	OUTPUT RANGE STND. DEV.	INPUT RANGE STND. DEV.	OUTPUT RANGE STND. DEV.	INPUT RANGE STND. DEV.	OUTPUT RANGE STND. DEV.
FILTER 4	0.1634	0.1634	110.7364	144.8444	110.7339	144.8549

TABLE XXXIV

FILTER 4 RANGE RATE STANDARD DEVIATIONS(FT./SEC.) AT 2500 SAMPLES/SEC.

	RUN 1 OUTPUT RANGE RATE STND. DEV.	RUN 2 OUTPUT RANGE RATE STND. DEV.	RUN 3 OUTPUT RANGE RATE STND. DEV.
FILTER 4	0.0	247907.688	247907.688

TABLE XXXV

FILTER 4 MAXIMUM RANGE(FT.) AND RANGE RATE(FT./SEC.) ERRORS AT 2500 SAMPLES/SEC.

	RUN 1		RUN 2		RUN 3	
	input = ramp		input = noise		input = ramp + noise	
	MAX RANGE ERROR	MAX RANGE RATE ERROR	MAX RANGE ERROR	MAX RANGE RATE ERROR	MAX RANGE ERROR	MAX RANGE RATE ERROR
FILTER 4	0.182×10^{-11}	0.320×10^{-8}	290.7632	501279.4	290.7632	501279.375

TABLE XXXVI

FILTER 4 RANGE AND RANGE RATE VARIANCE REDUCTION RATIOS AT 2500 SAMPLES/SEC.

	RUN 2		
	KR range variance reduction ratio	KRR range rate variance reduction ratio	τ Convergence Time (Sec.)
FILTER 4	1.712	5.012×10^{6}	<1

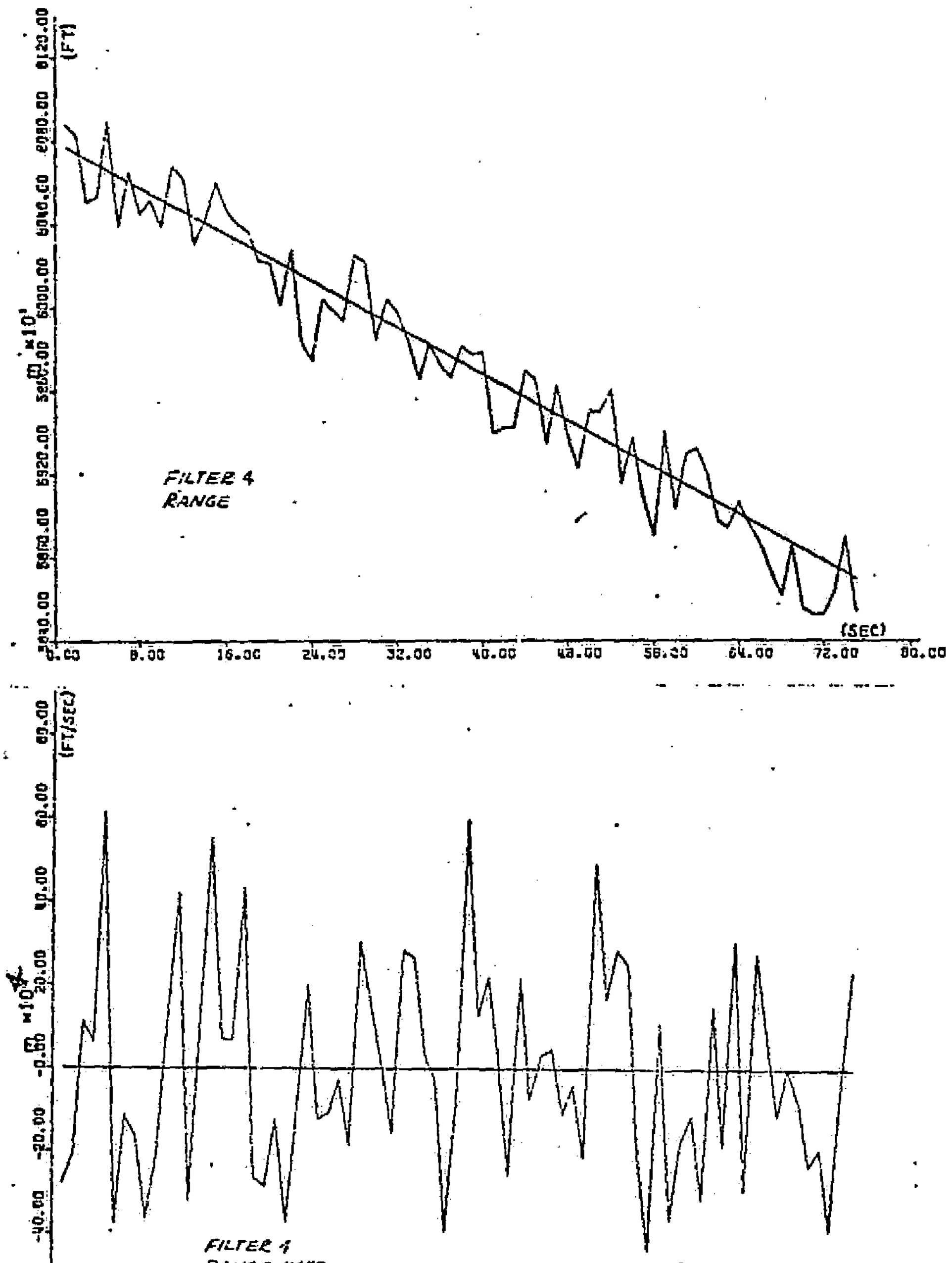


FIGURE 58 - Filter 4 at 2500 samples/sec.

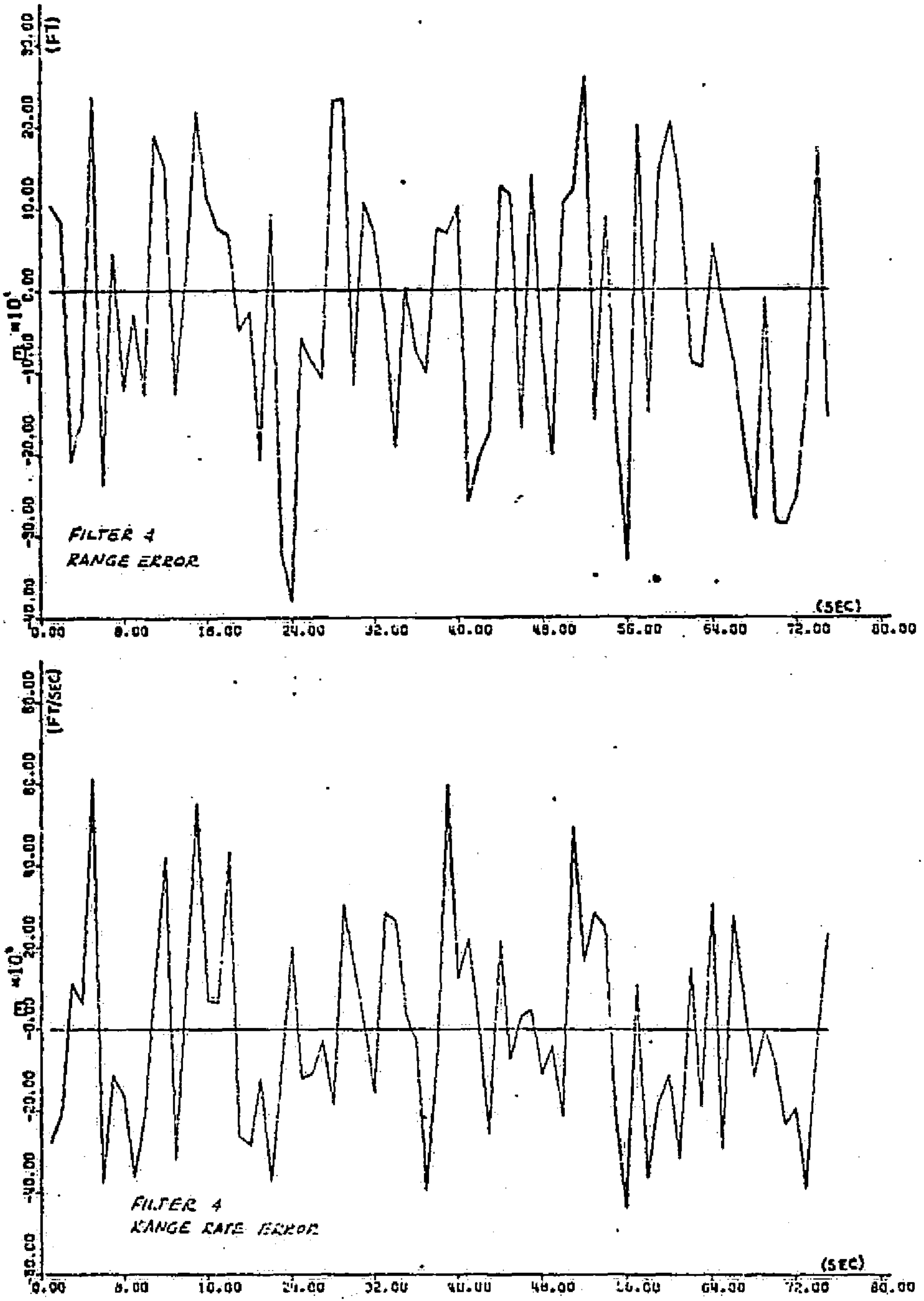


FIGURE 59 - Filter 4 at 2500 samples/sec.

TABLE XXXVII

FILTER 4 RANGE STANDARD DEVIATIONS(FT.) AT 6.25 SAMPLES/SEC.

	RUN 1 input = ramp		RUN 2 input = noise		RUN 3 input = ramp + noise	
	INPUT RANGE STND. DEV.	OUTPUT RANGE STND. DEV.	INPUT RANGE STND. DEV.	OUTPUT RANGE STND. DEV.	INPUT RANGE STND. DEV.	OUTPUT RANGE STND. DEV.
FILTER 4	65.3068	65.3068	91.3215	157.1930	115.2178	178.7200

TABLE XXXVIII

FILTER 4 RANGE RATE STANDARD DEVIATIONS(FT./SEC.) AT 6.25 SAMPLES/SEC.

	RUN 1 OUTPUT RANGE RATE STND. DEV.	RUN 2 OUTPUT RANGE RATE STND. DEV.	RUN 3 OUTPUT RANGE RATE STND. DEV.
FILTER 4	0.0	693.4480	693.4480

TABLE XXXIX

FILTER 4 MAXIMUM RANGE(FT.) AND RANGE RATE(FT./SEC.) ERRORS AT 6.25 SAMPLES/SEC.

	RUN 1 input = ramp		RUN 2 input = noise		RUN 3 input = ramp + noise	
	MAX RANGE ERROR	MAX RANGE RATE ERROR	MAX RANGE ERROR	MAX RANGE RATE ERROR	MAX RANGE ERROR	MAX RANGE RATE ERROR
FILTER 4	0.182×10^{-11}	0.580×10^{-11}	323.3982	1553.83	323.3982	1553.82

TABLE XL

FILTER 4 RANGE AND RANGE RATE VARIANCE REDUCTION RATIOS AT 6.25 SAMPLES/SEC.

	RUN 2		
	KR range variance reduction ratio	KRR range rate variance reduction ratio	τ Convergence Time (Sec.)
FILTER 4	2.9603	57.6609	2

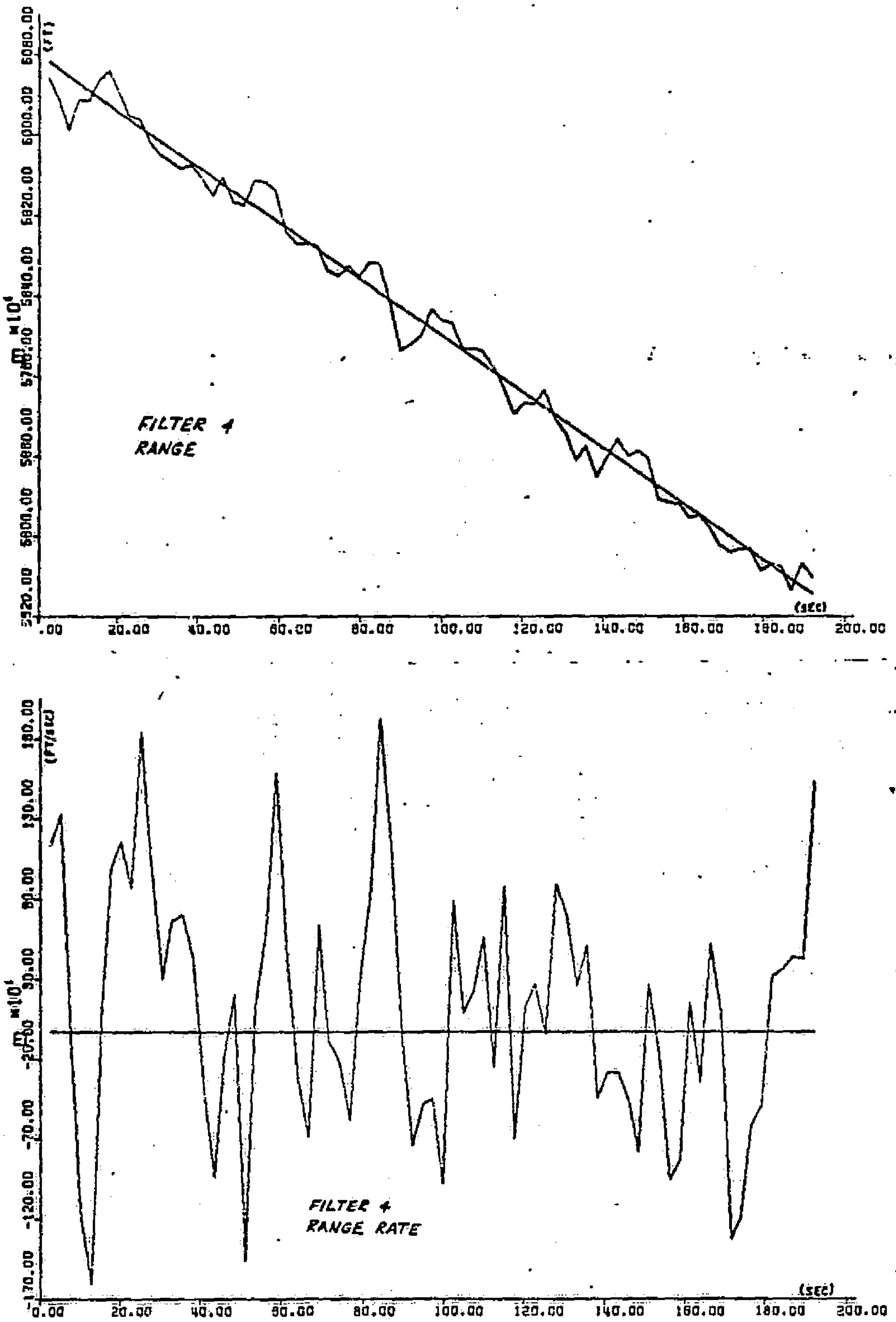


FIGURE 60 - Filter 4 at 6.25 samples/sec.

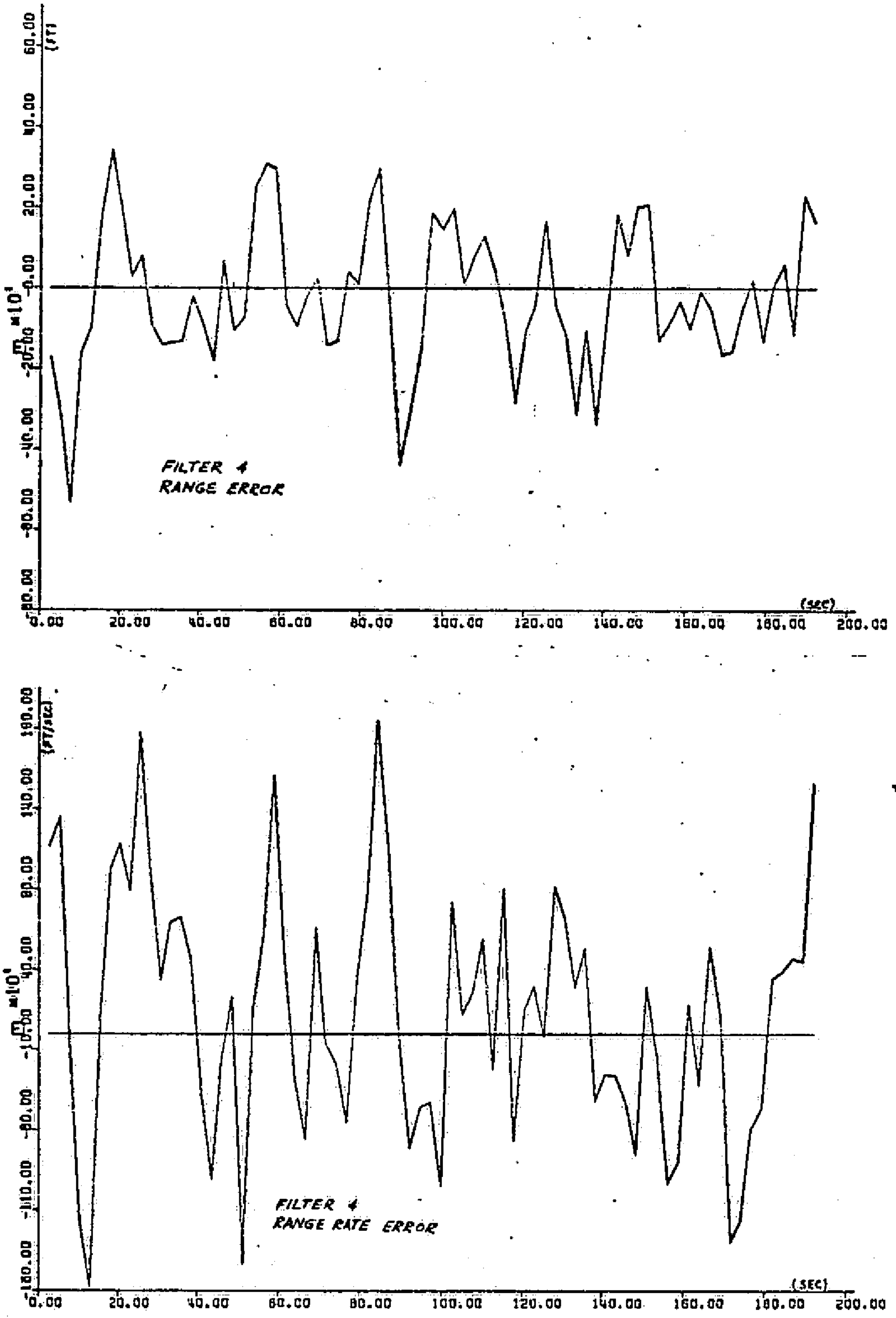


FIGURE 61 - Filter 4 at 6.25 samples/sec.

$$H_{RR} = \frac{RDOT}{RM} = \frac{1-0.75z^{-1}-1.5z^{-2}-2.25z^{-3}-4z^{-4}-2.25z^{-5}-1.5z^{-6}-0.75z^{-7}}{4DT(1-0.75z^{-1} + 0.25z^{-2} + 0.25z^{-3} + 0.25z^{-4})} \quad .(27)$$

The variance reduction ratios, KR and KRR, can be determined from the weighting sequences $h_R(i)$ and $h_{RR}(i)$ by

$$K = \sum_{i=0}^{\infty} h^2(i). \quad (28)$$

The program presented in Appendix D is used to evaluate this series. The resulting variance reduction ratios calculated are

$$KR = 48 \quad (29)$$

$$KRR(2500 \text{ samples/sec.}) = 1.47 \times 10^8 \quad (30)$$

$$KRR(6.25 \text{ samples/sec.}) = 916. \quad (31)$$

The variance reduction ratios presented in the tables for Filter 4 are calculated from actual simulation data. Although these are slightly better results than determined above, smoothing over four samples does not offer an adequate level of noise rejection.

5. Filter 5

Simulation data for Filter 5 is presented in Tables XLI - XLIV for 2500 samples/second and in Tables XLV - XLVIII for 6.25 samples/second. A graphical display of this data is presented in Figures 62 and 63 and in Figures 64 and 65 for 6.25 samples/second.

Filter 5 is a digital tracking filter employing skip sampling over sixteen samples. It is characterized by the transfer functions

$$H_R = \frac{RE}{RM} = \frac{23.5 + 23.5z^{-1} + \ldots + 23.5z^{-15} - 7.5z^{-16} - \ldots - 7.5z^{-31}}{256} \qquad (32)$$

and

$$H_{RR} = \frac{RDOT}{RM} = \frac{1 + z^{-1} + \ldots + z^{-15} - z^{-16} - \ldots - z^{-31}}{256\ DT} \qquad (33)$$

The program to evaluate variance reduction ratios (listed in Appendix D) using

$$K = \sum_{i=0}^{\infty} h^2(i) \qquad (28)$$

determined the ratios:

$$KR = 1.72 \times 10^{-1} \qquad (34)$$

$$KRR(2500\ \text{samples/sec.}) = 5.74 \times 10^{3} \qquad (35)$$

$$KRR(6.25\ \text{samples/sec.}) = 3.59 \times 10^{-2} \qquad (36)$$

These values are in close agreement with those derived from simulation data and presented in the tables for Filter 5. As with this type of filter the range rate variance reduction ratio is proportional to the square of the sampling rate while the range variance reduction ratio is independent of sampling rate.

TABLE XLI

FILTER 5 RANGE STANDARD DEVIATIONS(FT.) AT 2500 SAMPLES/SEC.

	RUN 1 input = ramp		RUN 2 input = noise		RUN 3 input = ramp + noise	
	INPUT RANGE STND. DEV.	OUTPUT RANGE STND. DEV.	INPUT RANGE STND. DEV.	OUTPUT RANGE STND. DEV.	INPUT RANGE STND. DEV.	OUTPUT RANGE STND. DEV.
FILTER 5	2.6123	2.6123	106.1125	39.3340	106.1860	39.3009

TABLE XLII

FILTER 5 RANGE RATE STANDARD DEVIATIONS(FT./SEC.) AT 2500 SAMPLES/SEC.

	RUN 1 OUTPUT RANGE RATE STND. DEV.	RUN 2 OUTPUT RANGE RATE STND. DEV.	RUN 3 OUTPUT RANGE RATE STND. DEV.
FILTER 5	0.0	5693.6289	5693.6289

TABLE XLIII

FILTER 5 MAXIMUM RANGE(FT.) AND RANGE RATE(FT./SEC.) ERRORS AT 2500 SAMPLES/SEC.

	RUN 1 input = ramp		RUN 2 input = noise		RUN 3 input = ramp + noise	
	MAX RANGE ERROR	MAX RANGE RATE ERROR	MAX RANGE ERROR	MAX RANGE RATE ERROR	MAX RANGE ERROR	MAX RANGE RATE ERROR
FILTER 5	0.0	0.207×10^{-8}	122.399	15702.340	122.399	15702.340

TABLE XLIV

FILTER 5 RANGE AND RANGE RATE VARIANCE REDUCTION RATIOS AT 2500 SAMPLES/SEC.

	RUN 2		
	KR range variance reduction ratio	KRR range rate variance reduction ration	τ Convergence Time (Sec.)
FILTER 5	1.374×10^{-1}	2.879×10^{3}	<1

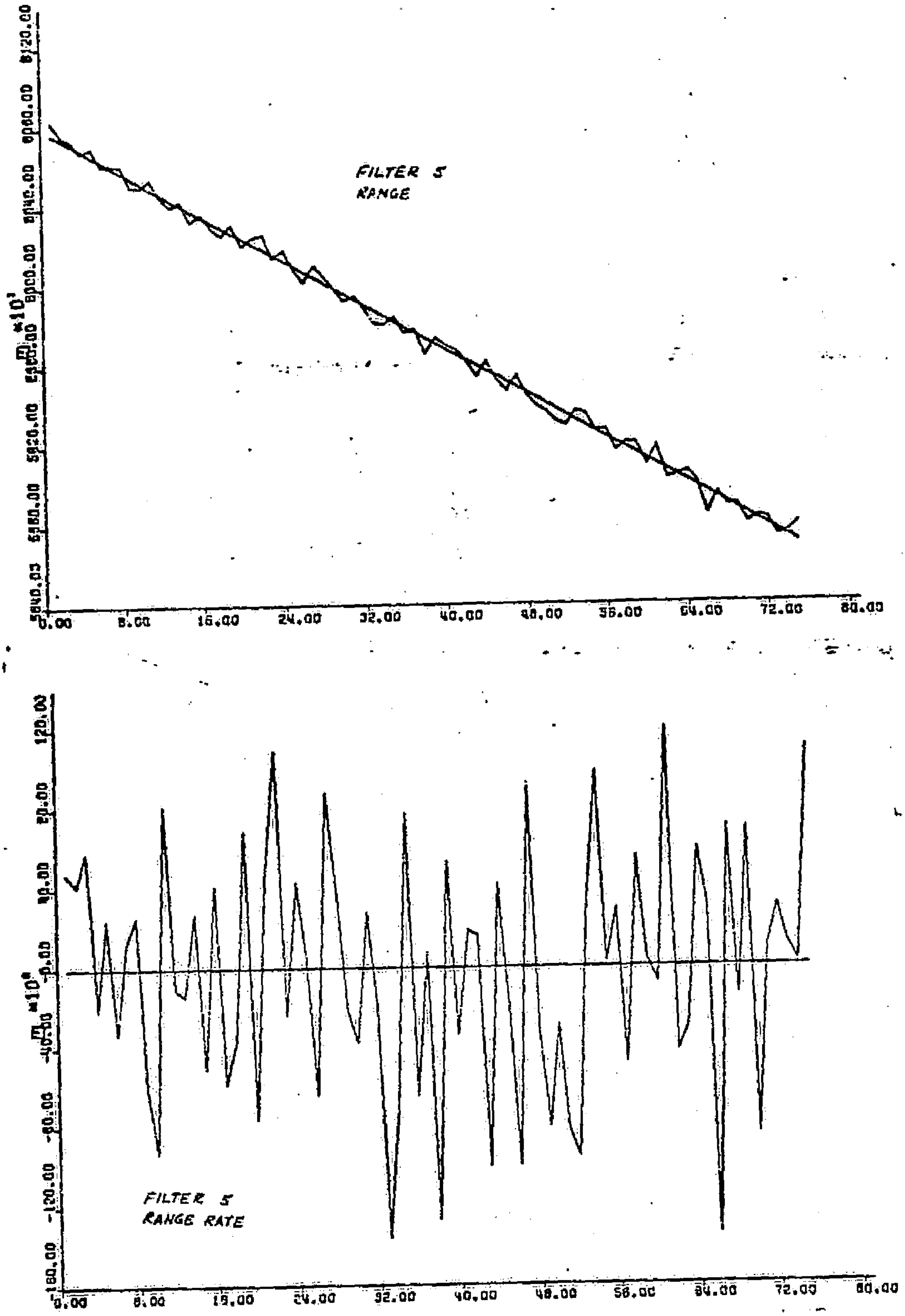


FIGURE 62 - Filter 5 at 2500 samples/sec.

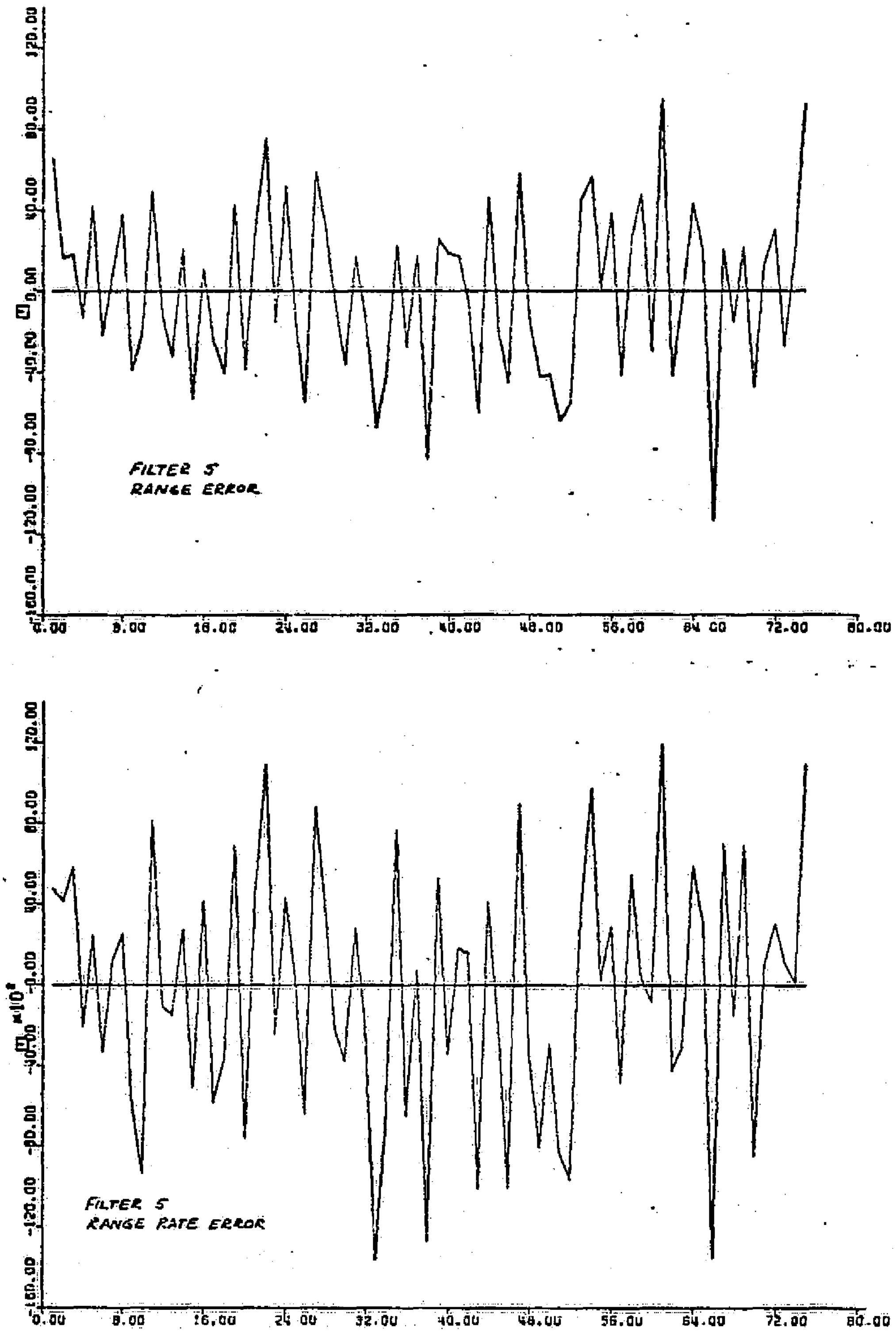


FIGURE 63 - Filter 5 at 2500 samples/sec.

TABLE XLV

FILTER 5 RANGE STANDARD DEVIATIONS(FT.) AT 6.25 SAMPLES/SEC.

	RUN 1 input = ramp		RUN 2 input = noise		RUN 3 input = ramp + noise	
	INPUT RANGE STND. DEV.	OUTPUT RANGE STND. DEV.	INPUT RANGE STND. DEV.	OUTPUT RANGE STND. DEV.	INPUT RANGE STND. DEV.	OUTPUT RANGE STND. DEV.
FILTER 5	1044.906	1044.96	112.3026	41.1501	1083.432	1044.917

TABLE XLVI

FILTER 5 RANGE RATE STANDARD DEVIATIONS(FT./SEC.) AT 6.25 SAMPLES/SEC.

	RUN 1 OUTPUT RANGE RATE STND. DEV.	RUN 2 OUTPUT RANGE RATE STND. DEV.	RUN 3 OUTPUT RANGE RATE STND. DEV.
FILTER 5	0.0	15.0085	15.0085

TABLE XLVII

FILTER 5 MAXIMUM RANGE(FT.) AND RANGE RATE(FT./SEC.) ERRORS AT 6.25 SAMPLES/SEC.

	RUN 1 input = ramp		RUN 2 input = noise		RUN 3 input = ramp + noise	
	MAX RANGE ERROR	MAX RANGE RATE ERROR	MAX RANGE ERROR	MAX RANGE RATE ERROR	MAX RANGE ERROR	MAX RANGE RATE ERROR
FILTER 5	0.909×10^{-12}	0.278×10^{-11}	122.002	37.450	122.0018	37.450

TABLE XLVIII

FILTER 5 RANGE AND RANGE RATE VARIANCE REDUCTION RATIOS AT 6.25 SAMPLES/SEC.

	RUN 2		
	KR range variance reduction ratio	KRR range rate variance reduction ration	τ Convergence Time (Sec.)
FILTER 5	1.342×10^{-1}	1.786×10^{-2}	5

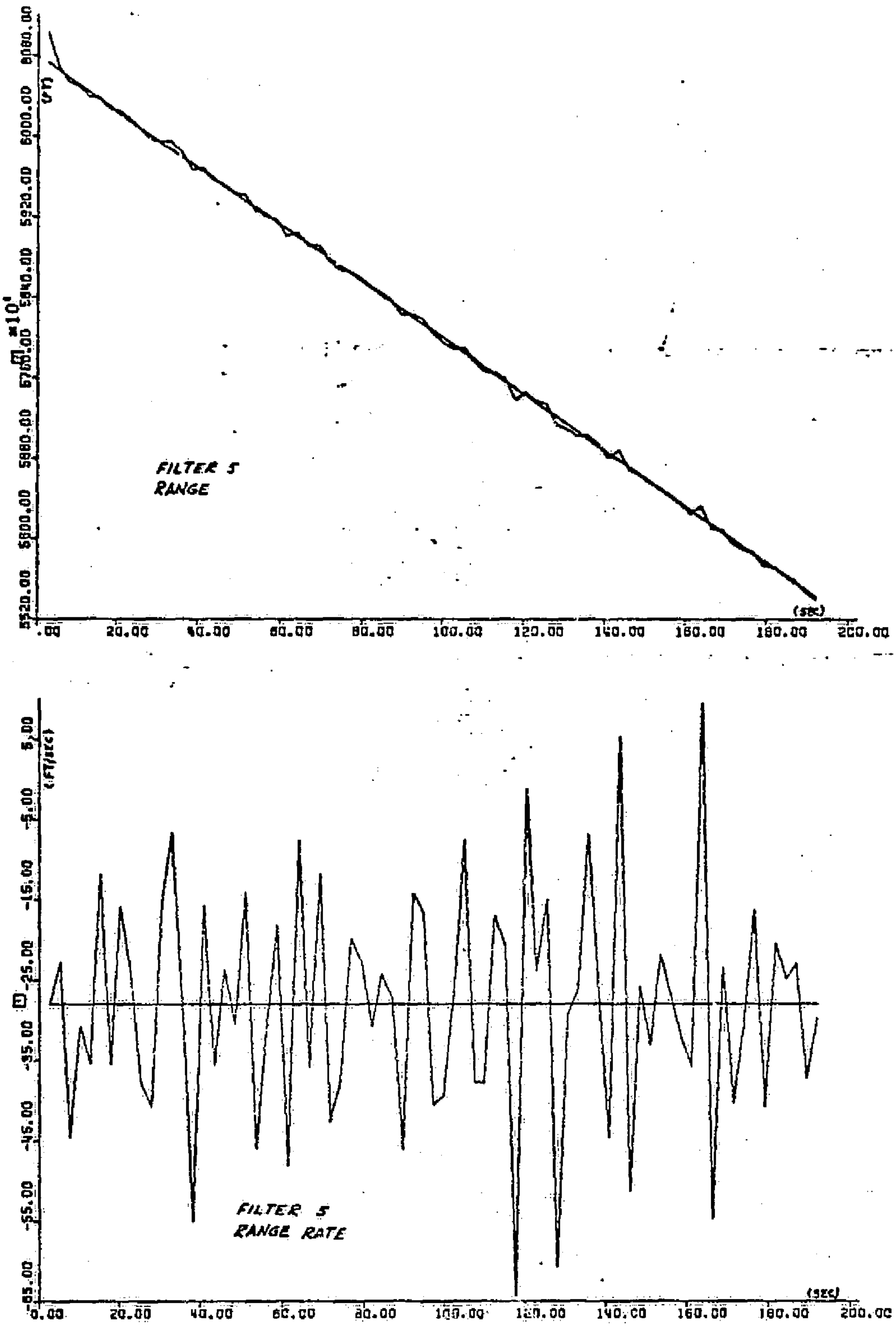


FIGURE 64 - Filter 5 at 6.25 samples/sec.

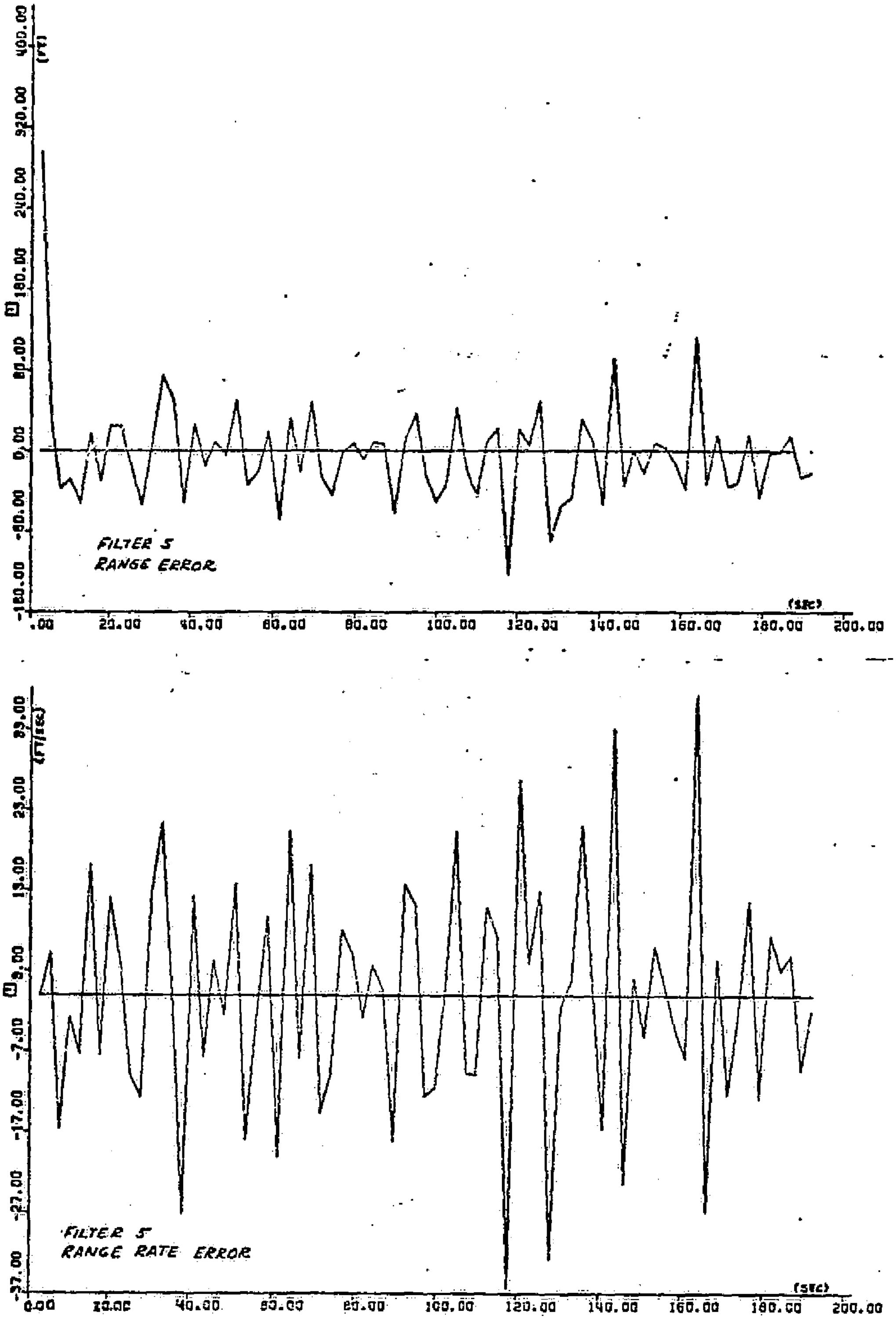


FIGURE 65 - Filter 5 at 6.25 samples/sec.

IV. MICROPROCESSOR SIMULATIONS

Two of the filter designs are selected to be implemented on a microprocessor based system. They are Filter 3 and Filter 5. Simulations are conducted in the same manner as is done on the IBM 370. The same range input signals are employed, and statistical analysis of the outputs is performed as was done in the IBM 370 simulation runs. This allows direct comparisons to be drawn.

The simulations are not conducted in real time. Considerations are taken for execution time, however, and are presented in the test results.

A. Description of Microprocessor System

The microprocessor simulations are conducted on an expanded version of the Motorola MEK 6800D2 Evaluation Kit II, a microcomputer system based on the Motorola MC 6800 microprocessing unit. The details of the revisions made to the system are outlined in the Motorola application note "MEK 6800D2 Microcomputer Kit System Expansion Techniques".[7] The basic system memory of 512 bytes of static RAM is replaced with 32 kilobytes of dynamic RAM. The MINIBUG III monitor ROM and its associated serial interface are added co-resident to the basic system's JBUG monitor ROM and serial interface. Under MINIBUG control the system is connected via RS-232 interface to a data terminal. Under JBUG control the audio cassette interface provides an inexpensive means of permanent storage.

B. Description of Simulating Programs

The software for implementing the algorithms for Filter 3 and Filter 5 is developed at the assembly language level. The primary considerations in its development are the one byte word size and the lack of a hardware multiplier on the 6800 microprocessor. The consequences of the small word size are that internal values must be represented in multiple byte lengths. Since these values can only be written into or read from memory one byte at a time, execution time is dependent on the number of bytes used to represent a value. For this reason, it is necessary to determine the minimum number of bytes needed to preserve precision at any given point in the program. Although the range input, range output and range rate output are two byte values, internal word size varies from two to five bytes.

Multiplications are handled by a multiplication subroutine. Under worst case conditions this routine requires 2,235 periods of the system clock to return a product. This represents a significant percentage of program execution time.

1. Program FILTER 3

An assembly language listing of the microprocessor realization of Filter 3 is presented in Appendix B. This program accepts a two byte unsigned binary word representing a noisy range value and outputs a two byte unsigned binary word representing the present estimated range and a two byte, two's complement binary word representing the present estimated range rate. When a noisy range value is received it is loaded onto the bottom of a 36 byte stack, REGS, containing the previous 17 noisy range inputs. A summation is then made of the six most recent entries onto the stack and subtracted from that is the summation of the six oldest entries on the stack. The result of these operations is a three byte, two's complement number stored in the variable TSUM. This value is multiplied by the scaled constant $(1/(72*DT)) * 2^{16}$ to determine the estimated range rate. The 2^{16} scaling factor is included in the constant because the constant is typically less than one. Since integer arithmetic is employed, tring to represent a number between zero and one by a zero or a one would cause a very significant loss of accuracy. To circumvent this situation the constant is premultiplied by a factor of 2^{16}, which is equivalent to shifting the constant two bytes to the left. After the multiplication of TSUM by the constant has been accomplished the two least significant bytes of the five byte product are truncated which is equivalent to a two byte shift back to the right. The magnitude of the estimated range rate is such that it can be represented sufficiently by a two byte value so the most significant byte of the three remaining bytes of the product can also be discarded. The end result is a two byte, two's complement number, RDOT, representing the estimated range rate.

TSUM is multiplied by the scaled constant $(7.5/72)*2^{16}$ to derive a range correction term, RCRCT, which will be used in the range calculations to give the estimated range. In this case, the two lowest significant bytes are retained until after the addition in the range calculations to preserve accuracy. However, the most significant byte can still be discarded leaving a four byte, two's complement term RCRCT.

To derive the estimated range, RE, the summation of the 16 most recent entries onto the stack REGS is taken. The result is a three byte number located in SUM. This value is multiplied by the scaled constant $(1/16)*2^{16}$ producing a five byte result. The most significant byte is discarded and the remaining four byte value is added to RCRCT. The two most significant bytes of the sum from this addition are the unsigned binary representation of the estimated range.

At this point FILTER 3 receives the next noisy range term and pushes it onto the bottom of the stack REGS causing the oldest entry on the stack to be lost off the top. The process of obtaining the estimated range and range rate is then repreated for these 18 entries on the stack.

Program FILTER 3 utilizes four subroutines: SHFTR, ADD, SUB and MULT. Subroutine SHFTR shifts all entries in the stack REGS up one and loads the latest range error term onto the bottom of the stack. Subroutine ADD adds two three-byte numbers. The numbers are entered into the subroutine through the variables A and B. The three byte sum is returned through the variable SUM. Subroutine SUB is a three byte subtraction routine. Values are entered and returned through the same variables used in subroutine ADD.

All multiplication required by FILTER 3 is performed by subroutine MULT, a two byte by three byte, two's complement multiplication routine. The two byte multiplicand is entered through MLTCD and the three byte multiplier is entered through MLTPR. The five byte product is returned through the variable PROD.

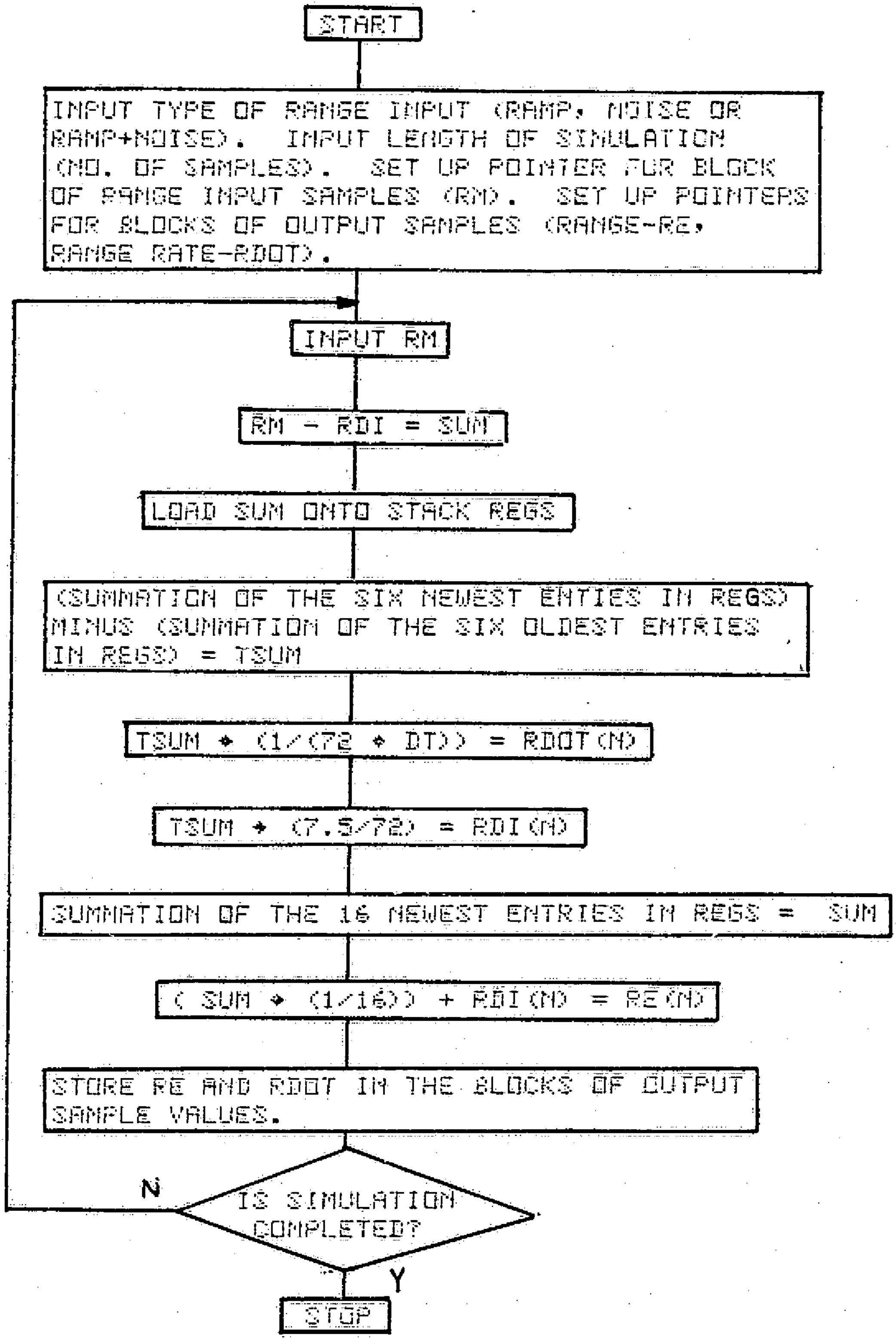


FIGURE 66 - Flowchart for program FILTER 3

Subroutine MULT also contains a rounding routine. Since one of the factors of PROD has been scaled up by 2^{16}, PROD must be scaled down by 2^{16} to obtain the correct result. Rather than truncating, PROD is rounded off to its three most significant bytes. The flag ROUND is used to turn the rounding routine on or off as needed.

To facilitate the display of data the FILTER DATA PRINTER program is appended to the FILTER 3 program. For each sample, the printer program lists the sample number, the value of the noisy range input at that sample, the value of the actual range at that sample and the estimated range and range rate calculated by FILTER 3. This program converts all hexidecimal values to decimal values.

2. Program FILTER 5

An assembly language listing of the microprocessor realization of Filter 5 is presented in Appendix C. This program accepts a two byte unsigned binary word representing a noisy range value. After receiving sixteen of these values the program outputs a two byte unsigned binary word representing the present estimated range and a two byte, two's compliment binary word representing the present estimated range rate. Also calculated but not output is a two byte unsigned binary word, RDI, representing the estimated range at a previous point in time. This value is subtracted from each incoming noisy range word to produce a two byte, two's complement binary range error term. These error terms are placed on a 32 byte stack, REGS. When sixteen noisy range samples have been received, REGS is then full and a summation of its contents is taken. The result is a 3 byte, two's complement binary value, TSUM, which is used to calculate the new estimated range rate, RDOT, and to update the two estimated range values, RE and RDI.

The estimated range rate, RDOT, is derived by multiplying TSUM by the scaled constant $(1/(256*DT))*2^{16}$. Since the constant is typically less than one and integer arithmetic is employed, the scale factor 2^{16} is included to maintain the two byte level of accuracy. The multiplication of the 2 byte constant and 3 byte TSUM results in a 5 byte product. The estimated range rate value is contained in the three most significant bytes of the product due to the scale factor included in the constant. This term can be accurately expressed in two bytes so that the most significant byte can also be discarded yielding a two byte, two's complement, estimated range rate value.

The three byte TSUM is then multiplied by the scaled constant $(1/16)*2^{16}$ and the resulting five byte product is reduced to two bytes in the same manner as described above. This two's complement number is added to the present value of RDI to update it for use in determining the range error terms for the next sixteen noisy range inputs. RDI is a two byte, unsigned binary value.

The estimated range, RE, is updated in the same manner. TSUM is muliptlied by the scaled constant $(23.5/256)*2^{16}$. The resulting five byte product is reduced to a two byte, two's complement number and added to the old value of RDI. The result of this addition is a two byte, unsigned binary number representing the current estimated range.

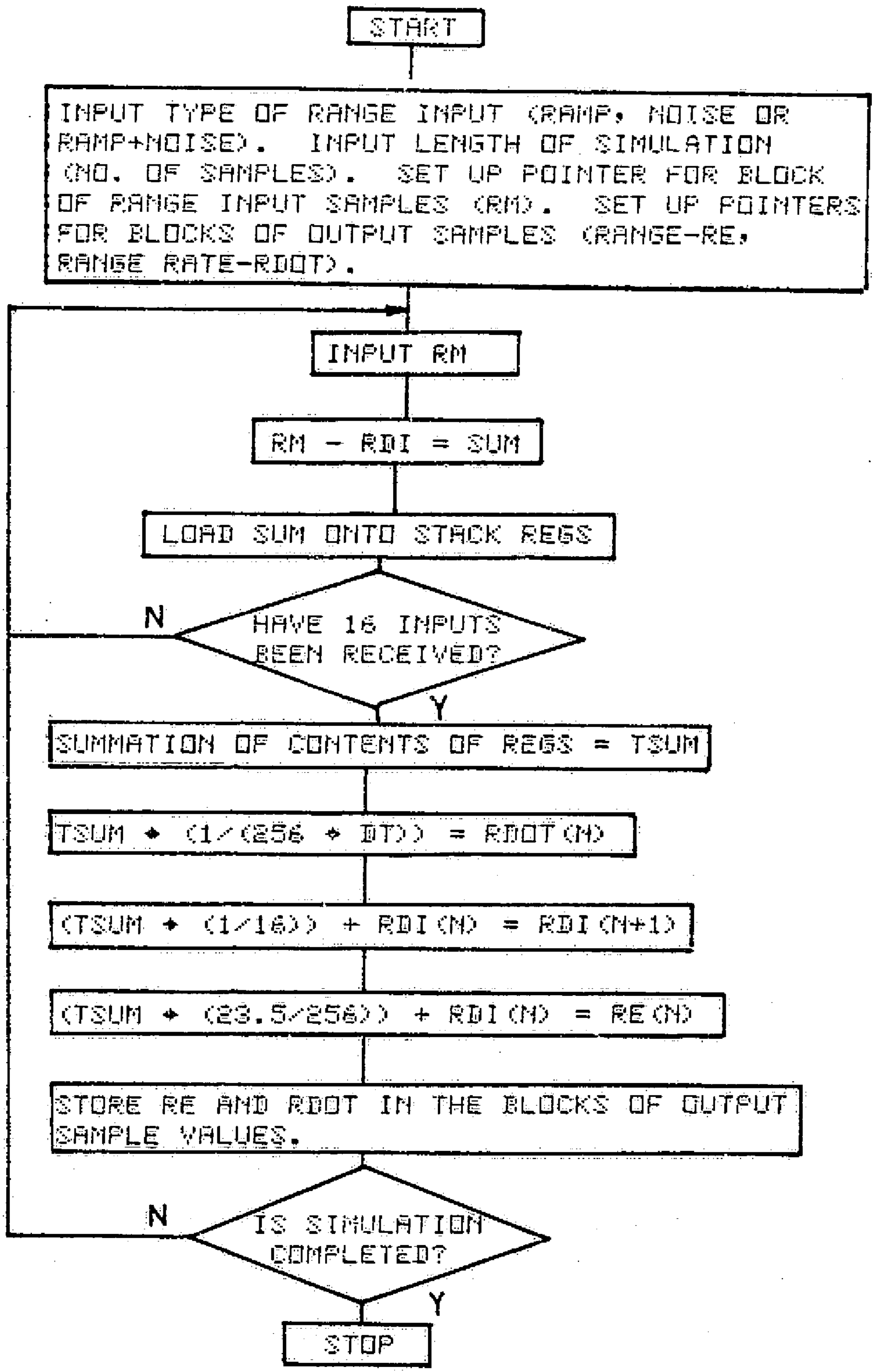


FIGURE 67 - Flowchart for program FILTER 5

Program FILTER 5 utilizes the same four subroutines used by Filter 3. The operation of these subroutines is exactly as described in the section on FILTER 3. Temporary storage is allocated for the stack REGS in such a way that subroutine SHFTR, which is responsible for pushing data onto the stack and shifting the other entries up, need not be changed to reflect the fact that REGS is a 36 byte stack in FILTER 3 and a 32 byte stack in FILTER 5. Both programs utilize premultiplication of constants by 2^{16} so that the rounding routine in subroutine MULT also need not be changed.

Since FILTER 5 outputs estimated range and range rate data only once every sixteen sample periods, the FILTER DATA PRINTER program is modified to display data for only those sample periods for which outputs are generated.

C. Test Conditions

As noted previously, test conditions for the microprocessor simulation runs are very similar to those used in the IBM 370 simulations. Tests are conducted for each of the three range input signals: the ramp, Gaussian noise and the summation of the ramp and noise. The tests are not conducted in real-time but rather a block of data containing sequential samples of the input is resident in memory. The simulating program steps through this block retrieving input values as needed. A block consists of 630 sampled range values taken at the sampling rate. Each value is a two byte unsigned binary word. These are rounded integer representations of the same sampled input values employed in the IBM 370 simulations.

The microprocessor simulations are conducted at the 6.25 samples/second sampling rate only. Although simulation at the higher sampling rate is possible, the speed limitations of the microprocessor would make a real-time system unrealizable. The two filter designs chosen both offer better noise rejection at the lower sampling rate.

D. Test Results

1. Filter 3

Simulation runs for Filter 3 are conducted for a duration of 200 sample periods. The last 50 sample values of the range input, estimated range and estimatedrange rate are statistically analyzed and presented in Tables XLIX - LI. Also presented is the data for an equivalent run on the IBM 370. The results indicate that the implementation of the filter on a microprocessor based system is accomplished without significant loss of accuracy.

Program FILTER 3 requires 15,777 cycles of the microprocessor system clock to compute estimated range and range rate values after being given a sampled range input. At the 614.4KHz clock rate of the MEK 6800D2 Evaluation Kit, the execution time is 25.68 milliseconds. The 160 millisecond sampling period provides more than adequate time for filter calculations, hence, this program could be employed in a real-time system.

2. Filter 5

Filter 5 simulations are conducted for a duration of 608 sample periods. Since this filter returns an output only once

TABLE XLIX

FILTER 3 RANGE STANDARD DEVIATIONS(FT.) AT 6.25 SAMPLES/SEC.

	RUN 1 input = ramp		RUN 2 input = noise		RUN 3 input = ramp + noise	
FILTER 3	INPUT RANGE STND. DEV.	OUTPUT RANGE STND. DEV.	INPUT RANGE STND. DEV.	OUTPUT RANGE STND. DEV.	INPUT RANGE STND. DEV.	OUTPUT RANGE STND. DEV.
MICROPROCESSOR	65.380	65.375	103.531	53.105	102.647	61.596
IBM 370	65.3068	65.3068	105.9378	53.1095	108.1119	68.1752

TABLE L

FILTER 3 RANGE RATE STANDARD DEVIATIONS(FT./SEC.) AT 6.25 SAMPLES/SEC.

FILTER 3	RUN 1 input = ramp OUTPUT RANGE RATE STND. DEV.	RUN 2 input = noise OUTPUT RANGE RATE STND. DEV.	RUN 3 input = ramp + noise OUTPUT RANGE RATE STND. DEV.
MICROPROCESSOR	0.0	33.288	33.132
IBM 370	0.0	33.1917	33.1917

TABLE LI

FILTER 3 RANGE AND RANGE RATE VARIANCE REDUCTION RATIOS AT 6.25 SAMPLES/SEC.

	RUN 2 input = noise		
FILTER 3	KR VARIANCE RANGE REDUCTION RATIO	KRR VARIANCE RANGE RATE REDUCTION RATIO	τ CONVERGENCE TIME (SEC.)
MICROPROCESSOR	2.632×10^{-1}	1.034×10^{-1}	3
IBM 370	2.513×10^{-1}	9.817×10^{-2}	3

for every sixteen sampled inputs, 38 output values are determined during a simulation run. The filter converges to steady state after two execution cycles (32 sample periods), therefore, the last 35 output values represent steady state and are statistically analyzed. This set of samples is of sufficient size to insure statistically accurate results. Data for the microprocessor simulations of Filter 5 and an equivalent IBM 370 run are presented in Tables LII - LIV. Here again, as in the microprocessor realization of Filter 3, results agree with those obtained on the IBM 370.

The worst case execution time for an "OFF" sample period, when no filter outputs are produced, is 907 cycles of the microprocessor system clock. The execution time for an "ON" sample period, when filter output values are determined, is 11,639 cycles of the system clock. At the 614.4KHz clock rate of the MEK 6800D2 Evaluation Kit, execution times are 1.48 and 18.94 milliseconds for "OFF" and "ON" sample periods, respectively. However, the 6800 family is capable of clock rates up to 2MHz which would yield execution times of 0.45 and 5.82 milliseconds for "OFF" and "ON" sample periods, respectively.

To offset the problem of smoothed range and range rate data being available only every sixteenth sample instant, it has been proposed that sixteen filters be operated in parallel with each filter lagging the next by one sample period.[8] In this manner an output from one of the filters would be available at each sample instant. At the 6.25 samples/second sampling rate

TABLE LII

FILTER 5 RANGE STANDARD DEVIATIONS(FT.) AT 6.25 SAMPLES/SEC.

FILTER 5	RUN 1 input = ramp		RUN 2 input = noise		RUN 3 input = ramp + noise	
	INPUT RANGE STND. DEV.	OUTPUT RANGE STND. DEV.	INPUT RANGE STND. DEV.	OUTPUT RANGE STND. DEV.	INPUT RANGE STND. DEV.	OUTPUT RANGE STND. DEV.
MICROPROCESSOR	734.514	734.516	91.516	32.489	755.846	735.662
IBM 370	734.5007	734.5007	111.0584	35.4184	739.8486	735.4358

TABLE LIII

FILTER 5 RANGE RATE STANDARD DEVIATIONS(FT./SEC.) AT 6.25 SAMPLES/SEC.

FILTER 5	RUN 1 input = ramp OUTPUT RANGE RATE STND. DEV.	RUN 2 input = noise OUTPUT RANGE RATE STND. DEV.	RUN 3 input = ramp + noise OUTPUT RANGE RATE STND. DEV.
MICROPROCESSOR	0.0	11.543	11.508
IBM 370	0.0	12.5710	12.5710

TABLE LIV

FILTER 5 RANGE AND RANGE RATE VARIANCE REDUCTION RATIOS AT 6.25 SAMPLES/SEC.

	RUN 2 input = noise		
FILTER 5	KR VARIANCE RANGE REDUCTION RATIO	KRR VARIANCE RANGE RATE REDUCTION RATIO	τ CONVERGENCE TIME (SEC.)
MICROPROCESSOR	1.260×10^{-1}	1.591×10^{-2}	5
IBM 370	1.017×10^{-1}	1.281×10^{-2}	5

the execution time of program FILTER 5 is only a fraction of the sampling period. Hence, the same processor can be used for all sixteen filters. In a given sampling period fifteen filters would be at "OFF" sampling periods while one would be at its "ON" sampling period. Operating with the 614.4KHz system clock, total execution time would be 42.62 milliseconds, slightly over a quarter of the sampling period.

CONCLUSIONS AND RECOMMENDATIONS

The IBM 370 simulations demonstrate that Filter 1 offers improved noise reduction at higher sampling rates in both the range and range rate modes for both constant gains and bandlimited differentiator. Maneuver-following capabilities, as measured by convergence time, are independent of sampling rate. Noise reduction for Filter 2, Filter 3 and Filter 5 is independent of sampling rate in the range mode and increases with decreasing sampling rate in the range rate mode. These filters all demonstrate increased maneuver-following capability at higher sampling rates. Filter 4 does not provide sufficient noise reduction to be considered further.

At the low sampling rate (6.25 samples/second) and with a short convergence time, Filter 5 has greater noise reduction than Filter 3. If parameter pairs are chosen for Filter 1 and Filter 2 to yield an equally short convergence time, they too do not provide the level of noise reduction of Filter 5. However, if a longer convergence time is allowed, the parameter pairs of Filter 1 and Filter 2 can be chosen to provide higher levels of noise reduction than Filter 5. In this case, Filter 1 (bandlimited differentiator) provides greater noise reduction than Filter 2 for a given convergence time.

The advantage of Filter 1 becomes more apparent at the higher sampling rate. Convergence time is unaffected but noise reduction increases with sampling rate. Hence, the capabilities of this filter are determined by the limitations of the processor with which it is implemented. Future generations of processors will offer faster clock rates which will allow a corresponding increase in sampling rates and result in better filter performance.

Filter performance can be summarized:

Filter 1: τ - independent of sampling rate
- dependent on K1, K2
KR - decreases with increasing sampling rate
- dependent on K1, K2
KRR - decreases with increasing sampling rate
- dependent on K1, K2
The tradeoff between τ and the ratios KR and KRR is controlled by K1, K2 (b in the BLD).

Filter 2: τ - decreases with increasing sampling rate
- dependent on α,β
KR - independent of sampling rate
- dependent on α,β
KRR - decreases with decreasing sampling rate
- dependent on α,β
The tradeoff between τ and the ratios KR and KRR is controlled by α,β.

Filter 3: τ - decreases with increasing sampling rate
KR - dependent on sampling rate slightly, due to updating
KRR - decreases with decreasing sampling rate

Filter 5: τ - decreases with increasing sampling rate
KR - independent of sampling rate
KRR - decreases with decreasing sampling rate.

Future study should be directed toward implementation of Filter 1 or Filter 2 at a higher sampling rate with a 16 bit microprocessor having a hardware multiplier. It would also be worthwhile to investigate different methods of approximating the continuous system of Filter 1 with discrete systems. The method used in this study is only one way of mapping from the s-plane to the z-plane. Other methods should be examined to determine if any offer mappings more suitable for this application.

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APPENDIX A

The following pages contain a FORTRAN listing of program FLT, the associated CALC subroutines for each of the five filters and the two plotting subroutines, PLOTB and MCPLOT.

```
C
C    THIS PROGRAM SIMULATES A DIGITAL FILTER.
C   THE PARAMETERS OF THE FILTER AND INITIAL CONDITIONS ARE READ IN
C   ON NAMELIST LIST.
C   THE PLOTTING PARAMETERS ARE READ IN ON NAMELIST DIM.
C   THE PARAMETERS OF THE RANDOM NUMBER GENERATOR ARE READ IN CN
C   NAMELIST XRAND.
C   SUBROUTINE CALC PERFORMS ALL FILTER CALCULATIONS.
C   SUBROUTINE GGNRF GENERATES THE NORMALLY DISTRIBUTED RANDOM VARIABLES
C   THAT ARE USED AS RANGE NOISE.
C   SUBROUTINE BECORI CALCULATES THE MEAN AND STANDARD DEVIATION OF THE
C   INPUT RANGE, OUTPUT RANGE AND OUTPUT RANGE RATE.
C   SUBROUTINE PLOTB FORMATS DATA TO USE THE PRINTER FOR PLOTTING.
C   SUBROUTINE MCPLOT FORMATS DATA FOR THE CALCOMP PLOTTER.
C
C   PROGRAM FLT MAKES THREE FILTER SIMULATION RUNS FOR EACH SET OF
C   FILTER PARAMETERS.  A NEW SET OF FILTER PARAMETERS IS READ IN EVERY
C   TIME NAMELIST LIST IS READ.  THE FIRST SIMULATION RUN IS MADE WITH A
C   RAMP INPUT.  DATA FROM THIS RUN IS TABULATED IN A TABLE ONLY (NO
C   PLOTS).  THE SECOND SIMULATION RUN IS MADE WITH AN INPUT OF GAUSSIAN
C   NOISE.  DATA FROM THIS RUN IS ALSO TABULATED IN A TABLE ONLY.
C   THE THIRD SIMULATION RUN IS MADE WITH THE INPUT OF A NOISY  RAMP.
C   DATA FROM THIS RUN IS TABULATED IN A TABLE AND ALSO PLOTTED.
C   THE PLOTS RETURNED ARE DETERMINED BY THE PARAMETERS IN NAMELIST DIM.
C   ALL PLOTS ARE OF A FUNCTION VERSUS TIME.
C
C   NAMELIST LIST
C      LIST IS READ AT THE BEGINNING OF EACH RUN THROUGH THE MAIN PROGRAM
C           DRE = INITIAL ESTIMATE OF RANGE
C           DRDOT = INITIAL ESTIMATE OF RANGE RATE
C           DT = TIME BETWEEN INPUT SAMPLES
C           K1 AND K2 = PARAMETERS OF FILTER
C           DR = INITIAL RANGE
C           DV = INITIAL RANGE RATE
```

```
C          NDN = NJMBER OF FILTERS TO BE SIMULATED  (THE NUMBE3 OF TIMES
C                NAMELIST LIST IS TO 3E READ.)
C          IDI = NUMBER OF SAMPLE PERIODS BETWEEN THE READING OUT OF
C                 RESULTS
C          IDRI = NUMBER OF RESULTS TO BE READ OUT
C
C  NAMELIST DIM
C     DIM IS READ ONLY ONCE.
C          PLR = 1  SPECIFIES THE OUTPUT OF TWO RANGE PLOTS.  BOTH
C                PLOTS CONTAIN THREE FUNCTIONS-R,RM AND RE.  THE FIRST
C                PLOT USES A SCALE CHOSEN FROM THE MAX AND MIF FUNCTION
C                VALUES.  THE SECOND USES BU1 AND BL1 AS THE PLOT'S MAX
C                AND MIN VALUES.  IF PLR IS NOT SPECIFIED NO RANGE PLOTS
C                ARE GIVEN.  THE PLOTS ARE GENERATED AFTER THE THIRD
C                FILTER SIMULATION RUN FOR EACH FILTER.
C          PLRR = 1 SPECIFIES THE OUTPUT OF TWO RANGE RATE PLOTS.  BOTH
C                 PLOTS CONTAIN TWO FUNCTIONS-V AND RDOT.  THE FIRST
C                 PLOT USES A SCALE CHOSEN FROM THE MAX AND MIN FUNCTION
C                 VALUES.  THE SECOND USES BU2 AND BL2 AS THE PLOT'S MAX
C                 AND MIN VALUES.  IF PLR IS NOT SPECIFIED NO 3ANGE RATE
C                 PLOTS ARE GIVEN.  THE PLOTS ARE GENERATED AFTER THE
C                 THIRD FILTER SIMULATION RUN FOR EACH FILTER.
C          PLRER = 1 SPECIFIES THE OUTPUT OF ONE OR TWO RANGE ERROR
C                  PLOTS.  UNLIKE THE FIRST TWO SETS OF PLOTS, THESE ARE
C                  NCT GENERATED UNTILL ALL FILTERS HAVE BEEN 3UN.
C                  HENCE, THE RANGE ERROR FOR THE THIRD SIMULATION RUN
C                  FOR EACH FILTER APPEARS ON THE SAME PLOT.  THIS IS
C                  FOR COMPARISON PURPOSES.  THE FIRST
C                  PLOT USES A SCALE CHOSEN FROM THE FUNCTION'S MAX AN3
C                  MIN VALUES.  THE SECOND USES BU3 AND BL3 AS THE
C                  PLOT'S MAX AND MIN VALUES.  IF PLRER IS NOT SPECIFIED
C                  NO RANGE ERROR PLOTS ARE GENERATED.
C          PLRRER = 1 SPECIFIES THE OUTPUT OF ONE OR TWO RANGE RATE
C                   ERROR PLOTS.  THESE ARE ALSO NOT GENERATED UNTIL ALL
```

```
C                   FILTERS HAVE BEEN RUN.  HENCE, THE RANGE RATE ERROR
C                   FOR THE THIRD SIMULATION RUN FOR EACH FILTER APPEARS
C                   ON THE SAME PLOT.  THE FIRST
C                   PLOT USES A SCALE CHOSEN FROM THE FUNCTION'S MAX AND
C                   MIN VALUES.  THE SECOND USES BU4 AND BL4 AS THE
C                   PLOT'S MAX AND MIN VALUES.  IF PLRRER IS NOT
C                   SPECIFIED NO RANGE RATE ERROR PLOTS ARE GENERATED.
C          BU1 AND BL1 = THE UPPER AND LOWER LIMITS ON THE SECOND GRAPH
C                        OF THE RANGE DATA.  IF NOT SPECIFIED THEY ARE
C                        SET
C                           BU1 = (MEDIUM ACTUAL RANGE) + SPAN1
C                           BL1 = (MEDIUM ACTUAL RANGE) - SPAN1
C                        WHERE SPAN1 IS A MAIN PROGRAM CONSTANT.
C          BU2 AND BL2 = THE UPPER AND LOWER LIMITS ON THE SECOND GRAPH
C                        OF THE RANGE RATE DATA.  IF NOT SPECIFIED THEY
C                        ARE INTERNALLY SET
C                           BU2 = (MEDIUM ACTUAL RANGE) + SPAN2
C                           BL2 = (MEDIUM ACTUAL RANGE) - SPAN2
C                        WHERE SPAN2 IS A MAIN PROGRAM CONSTANT.
C          BU3 AND BL3 = THE UPPER AND LOWER LIMITS ON THE SECOND PLOT
C                        OF THE RANGE ERROR FUNCTION.  IF NOT SPECIFIED,
C                        A SECOND PLOT IS NOT GENERATED.
C          BU4 AND BL4 = THE UPPER AND LOWER LIMITS ON THE SECOND PLOT
C                        OF THE RANGE RATE ERROR FUNCTION.  IF NOT
C                        SPECIFIED, A SECOND PLOT IS NOT GENERATED.
C          CALCOM = 1 CREATES CALCOMP PLOTS.  A RANGE PLOT AND RANGE
C                     RATE PLOT AFTER THE THIRD SIMULATION RUN FOR EACH
C                     FILTER.  THE RANGE ERROR AND RANGE RATE ERROR
C                     PLOTS ARE GENERATED AFTER ALL FILTERS HAVE BEEN
C                     RUN.  HENCE, THESE PLOTS CONTAIN THAT DATA FROM
C                     THE THIRD SIMULATION RUN FOR EACH FILTER.  THIS
C                     IS FOR COMPARISON PURPOSES.
C
```

```
C
C          *NOTE*  INTERNAL SPECIFICATION OF BU1,BL1,BU2 AND BL2 CAN
C                  ONLY BE USED WHEN NO ACCELERATION IS ADDED.  IF THE
C                  VALUES OF SPAN1 AND SPAN2 ARE NOT ADEQUATE, THEY MAY
C                  BE CHANGED BY ALTERING THEIR VALUE IN THE MAIN
C                  PROGRAM.
C
C  NAMELIST XRAND
C     XRAND IS READ ONLY ONCE .
C          XM = THE MEAN OF THE NORMALLY DISTRIBUTED RANDOM VARIABLES
C          XDEV = THE STANDARD DEVIATION OF THE NORMALLY DISTRIBUTED
C                 RANDOM VARIABLES
C
C  INTERNAL PARAMETERS
C          NN = 0 TO NDN, NUMBER OF FILTERS THAT HAVE BEEN SIMULATED.
C          L = 0 TO IDRI, NUMBER OF TIMES SUBROUTINE CALC IS CALLED
C              (ONE DATA POINT IS GENERATED FOR EACH L)
C
C
C  PROGRAM FLT
C  DOUBLE PRECISION
      IMPLICIT REAL*8(D,K,R,V)
      INTEGER PLR,PLRR,PLRER,PLRRER,RUN
      DIMENSION TIMA(500)
      DIMENSION X(50,5),DIFF(5,500),RERR(5,500),Y(2500)
      DIMENSION RNG(5,500),RNGR(5,500),TIME(500)
      DIMENSION SNG(5,500),SNGR(5,500),SIFF(5,500),SERR(5,500)
      DIMENSION Z(6,6),XMI(6),SDI(6)
C  MATIX Z IS A DUMMY VARIABLE USED IN BECORI.
      NAMELIST/LIST/DRE,DRDOT,DT,K1,K2,DR,DV,NDN,IDI,IDRI
      NAMELIST/DIM/PLR,PLRR,PLRER,PLRRER,BU1,BL1,BU2,BL2,BU3,BL3,BU4,BL4
     2,CALCOM
      NAMELIST/XRAND/XM,XDEV
      CALL PLOTS (1024,4096)
```

```
      CALL PLTMSG ('*** DON FLEISCHER PLOTS READY ***',33)
      CALL PLOT (0.0,-11.0,-3)
      CALL PLOT (0.0,1.0,-3)
      NN = 0
      BU1 = 0.0
      BL1 = 0.0
      BU2 = 0.0
      BL2 = 0.0
      BU3 = 0.0
      BL3 = 0.0
      BU4 = 0.0
      BL4 = 0.0
      PLR = 0
      PLRR = 0
      PLRER = 0
      PLRRER = 0
      CALCOM = 0.0
      CALL GGNRF1(DSEED)
      READ(5,DIM)
      READ(5,XRAND)
100   READ(5,LIST)
      NN = NN+1
      BETA = IDI*DT
110   RUN = 1
      RE = DRE
      RDOT = DRDOT
      R = DR
      V = DV
      XXM = XM
      XXDEV = XDEV
      XM = 0.0
      XDEV = 0.0
      GOTO 140
120   RUN = 2
```

```
      CALL GGNRF2(DSEED)
      RE = 0.0
      RDOT = 0.0
      R = 0.0
      V = 0.0
      XM = XXM
      XDEV = XXDEV
      GOTO 140
 130  RUN = 3
      CALL GGNRF2(DSEED)
      RE = DRE
      RDOT = DRDOT
      R = DR
      V = DV
 140  CONTINUE
      WRITE(6,150)
 150  FORMAT(1H0,2X,'LIST')
      WRITE(6,160) RE,RDOT,DT,K1,K2,R,V,NDN,IDI,IDRI
 160  FORMAT(1H0,4X,'RE = ',G20.9/5X,'RDOT = ',G20.9/5X,'DT = ',G20.9/5X
     2,'K1 = ',G20.9/5X,'K2 = ',G20.9/5X,'R = ',G20.9/5X,'V = ',G20.9/5X
     3,'NDN = ',I11/5X,'IDI = ',I11/5X,'IDRI = ',I11///)
      WRITE(6,170)
 170  FORMAT(1H0,2X,'XRAND')
      WRITE(6,180) XM,XDEV
 180  FORMAT(1H0,4X,'XM = ',G20.9/5X,'XDEV = ',G20.9)
      IF(RUN .NE. 3) GOTO 300
C
C  CALCULATION OF BU1,BL1,BU2 AND BL2 IF NOT GIVEN AS A INPUT
C
      IF (BU1 .NE. 0.0  .OR.  BL1 .NE. 0.0) GOTO 190
      SPAN1 = 1000.0
      BU1 = R + V*IDI*DT*IDRI/2 + SPAN1
      BL1 = BU1 - 2*SPAN1
 190  IF (BU2 .NE. 0.0  .OR.  BL2 .NE. 0.0) GOTO 200
      SPAN2 = 2.0
```

```
      BU2 = V + SPAN2
      BL2 = V - SPAN2
 200  WRITE(6,210)
 210  FORMAT(1H0,2X,'DIM')
      WRITE(6,220) PLR,PLRR,PLRER,PLRRER,BU1,BL1,BU2,BL2
 220  FORMAT(1H0,4X,'PLR = ',I6/5X,'PLRR = ',I6/5X,'PLRER = ',I6/5X,'PLR
     2RER = ',I6/5X,'BU1 = ',G20.9/5X,'BL1 = ',G20.9/5X,'BU2 = ',G20.9/5
     3X,'BL2 = ',G20.9)
      IF (BU3 .EQ. 0.0  .AND.  BL3 .EQ. 0.0) GO TO 240
      WRITE(6,230) BU3,BL3
 230  FORMAT(1H0,4X,'BU3 = ',G20.9/5X,'BL3 = ',G20.9)
      GOTO 260
 240  WRITE(6,250)
 250  FORMAT(1H0,4X,'BU3 AND BL3 WERE NOT SPECIFIED IN DIM')
 260  IF (BU4 .EQ. 0.0  .AND.  BL4 .EQ. 0.0) GO TO 280
      WRITE(6,270) BU4,BL4
 270  FORMAT(1H0,4X,'BU4 = ',G20.9/5X,'BL4 = ',G20.9///)
      GOTO 300
 280  WRITE(6,290)
 290  FORMAT(1H0,4X,'BU4 AND BL4 WERE NOT SPECIFIED IN DIM'///)
 300  CONTINUE
      L = 0
      WRITE(6,310)
 310  FORMAT(1H0,2X,'TIME',17X,'R',17X,'RE',15X,'RERR',15X,'V',15X,'RDOT
     2',15X,'DIFF')
      RDI = 0.0
      RVI = 0.0
C
C  AN IF STATEMENT WILL BE INSERTED HERE TO CHECK TO SEE IF THE RANDOM
C  NUMBER GENERATOR IS TO BE USED ON THIS RUN.  IF IT IS, THE FOLLOWING
C  LOOP WILL BE SKIPPED.
C
 320  IF (XDEV .NE. 0.0)  GO TO 340
      DO 330 LAP = 1,IDI
      Y(LAP) = 0.0
 330  CONTINUE
```

```
      GOTO 350
C
C  THE CALL STATEMENT FOR THE RANDOM NUMBER GENERATOR WILL BE
C  HERE.  THIS SUBROUTINE WILL BE CALLED EACH TIME CALC IS CALLED.
C
 340  CALL GGNRF (IDI,Y)
      DO 350 LAP = 1,IDI
      Y(LAP) = XM + XDEV*Y(LAP)
 350  CONTINUE
      L = L+1
      TIME(L) = IDI*DT*L
      CALL CALC(R,V,DT.X,IDI,RE,RDOT,K1,K2,RDI,RVI,L,RM,Y,IDRI)
C
C  VARIABLES BEGINNING WITH R OR D ARE DOUBLE PRECISION.  THEY ARE USED
C  IN DATA TABLE OUTPUT.  VARIABLES BEGINNING WITH S ARE SINGLE
C  PRECISION.  THEY ARE USED IN THE PLOT OUTPUT.
C
C  RNG CONTAINS 3 FUNCTIONS TO BE PLOTTED ON THE RANGE GRAPH.
      RNG(1,L) = RE
      RNG(2,L) = R
      RNG(3,L) = RM
      SNG(1,L) = RE
      SNG(2,L) = R
      SNG(3,L) = RM
C  RNGR CONTAINS 2 FUNCTIONS TO BE PLOTTED ON THE RANGE RATE GRAPH.
       RNGR(1,L) = RDOT
       RNGR(2,L) = V
       SNGR(1,L) = RDOT
       SNGR(2,L) = V
C  RERR CONTAINS 1 FUNCTION  TO BE PLOTTED ON THE RANGE ERROR GRAPH.
      RERR(NN,L) = RE - R
      SERR(NN,L) = RE - R
C  DIFF CONTAINS 1 FUNCTION  TO BE PLOTTED ON THE RANGE
C  RATE ERROR GRAPH.
      DIFF(NN,L) = RDOT - V
```

```
      SIFF(NN,L) = RDOT - V
C
      WRITE(6,360) TIME(L),R,RE,RERR(NN,L),V,RDOT,DIFF(NN,L)
  360 FORMAT(1H0,3X,G7.1,6(1X,G19.11))
      IF(L.LT.IDRI) GO TO 320
      RERRMX = 0.0
      DIFFMX = 0.0
      DO 370 LAP=1,50
      IF(ABS(X(LAP,4)).GT.RERRMX) RERRMX = ABS(X(LAP,4))
      IF(ABS(X(LAP,5)).GT.DIFFMX) DIFFMX = ABS(X(LAP,5))
  370 CONTINUE
      WRITE(6,380) RERRMX,DIFFMX
  380 FORMAT(1H0,4X,'MAXIMUM STEADY STATE RANGE ERROR = ',G20.9/5X,'MAXI
     1MUM STEADY STATE RANGE RATE ERROR = ',G20.9)
      CALL BECORI(X,50,3,50,XMI,SDI,Z,IER)
      WRITE(6,390) XMI(1),SDI(1)
  390 FORMAT(1H0,4X,'INPUT RANGE MEAN = ',G20.9/5X,'INPUT RANGE STND DEV
     1 = ',G20.9)
      WRITE(6,400) XMI(2),SDI(2)
  400 FORMAT(1H0,4X,'RANGE MEAN = ',G20.9/5X,'RANGE STND DEV = ',G20.9)
      WRITE(6,410) XMI(3),SDI(3)
  410 FORMAT(1H0,4X,'RANGE RATE MEAN = ',G20.9/5X,'RANGE RATE STND DEV =
     1 ',G20.9)
      IF(RUN .EQ. 1) GOTO 120
      IF(RUN .EQ. 2) GOTO 130
      IF(PLR .EQ. 0) GOTO 460
      CALL PLOTB (3,IDRI,BETA,SNG,TIME,0.0,0.0,0)
      WRITE(6,420)
      WRITE(6,430)
      WRITE(6,440)
      WRITE(6,450)
  420 FORMAT(1H0,26X,'****','FOR RANGE DATA',24X,'****')
  430 FORMAT(1H0,26X,'****','1 IS THE CALCULATED RANGE (RE)',8X,'****')
  440 FORMAT(1H0,26X,'****','2 IS THE ACTUAL RANGE (R)',13X,'****')
  450 FORMAT(1H0,26X,'****','3 IS THE NOISY RANGE (RM)',14X,'****')
```

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OF POOR QUALITY

```
      CALL PLOTB (3,IDRI,BETA,SNG,TIME,BU1,BL1,0)
      WRITE(6,420)
      WRITE(6,430)
      WRITE(6,440)
      WRITE(6,450)
460   IF(PLRR .EQ. 0) GOTO 500
      CALL PLOTB (2,IDRI,BETA,SNGR,TIME,0.0,0.,0)
      WRITE(6,470)
      WRITE(6,480)
      WRITE(6,490)
470   FORMAT(1H0,26X,'****','FOR RANGE RATE DATA',19X,'****')
480   FORMAT(1H0,26X,'****','1 IS THE CALCULATED RANGE RATE (RDOT)',1X,'*
     2**')
490   FORMAT(1H0,26X,'****','2 IS THE ACTUAL RANGE RATE (V)',8X,'****')
      CALL PLOTB (2,IDRI,BETA,SNGR,TIME,BU2,BL2,0)
      WRITE(6,470)
      WRITE(6,480)
      WRITE(6,490)
500   CONTINUE
      IF(CALCOM .EQ. 0.0) GOTO 510
      CALL MCPLOT(SNG,TIME,IDRI,2,0,SW,DATA)
      CALL MCPLOT(SNGR,TIME,IDRI,2,0,SW,DATA)
      IDRII = IDRI - 15
      DO 505 I=1,IDRII
      IA = I + 15
      TIMA(I) = TIME(IA)
      SNG(1,I) = SNG(1,IA)
      SNG(2,I) = SNG(2,IA)
      SNGR(1,I) = SNGR(1,IA)
      SNGR(2,I) = SNGR(2,IA)
505   CONTINUE
      CALL MCPLOT(SNG,TIMA,IDRII,2,0,SW,DATA)
      CALL MCPLOT(SNGR,TIMA,IDRII,2,0,SW,DATA)
510   IF(NN .LT. NDM) GOTO 100
      IF (PLRER .EQ. 0) GO TO 530
```

```
      CALL PLOTB (NDN,IDRI,BETA,SERR,TIME,0.0,0.0,1)
      WRITE(6,520)
 520  FORMAT(1H0,26X,'****','FOR RANGE ERROR (RERR)',16X,'****')
      IF (BU3 .EQ. 0.0  .AND.  BL3 .EQ. 0.0) GO TO 530
      CALL PLOTB (NDN,IDRI,BETA,SERR,TIME,BU3,BL3,1)
      WRITE(6,520)
 530  IF (PLRRER .EQ. 0) GO TO 550
      CALL PLOTB (NDN,IDRI,BETA,SIFF,TIME,0.0,0.0,1)
      WRITE(6,540)
 540  FORMAT(1H0,26X,'****','FOR RANGE RATE ERROR (DIFF)',11X,'****')
      IF (BU4 .EQ. 0.0  .AND.  BL4 .EQ. 0.0) GO TO 550
      CALL PLOTB (NDN,IDRI,BETA,SIFF,TIME,BU4,BL4,1)
      WRITE(6,540)
  550  CONTINUE
      IF (CALCOM .EQ. 0.0) GOTO 570
C  THIS LOOP GENERATES A ZERO REFERENCE LINE FOR THE CALCOMP PLOT.
      NDN1 = NDN + 1
      DO 560 L=1,IDRI
      SERR(NDN1,L) = 0.0
 560  SIFF(NDN1,L) = 0.0
      CALL MCPLOT(SERR,TIME,IDRI,NDN1,0,SW,DATA)
      CALL MCPLOT(SIFF,TIME,IDRI,NDN1,0,SW,DATA)
      DO 567 J=1,NDN1
      DO 565 I=1,IDRII
      IA = I + 15
      SIFF(J,I) = SIFF(J,IA)
      SERR(J,I) = SERR(J,IA)
 565  CONTINUE
 567  CONTINUE
      CALL MCPLOT(SERR,TIMA,IDRII,NDN1,0,SW,DATA)
      CALL MCPLOT(SIFF,TIMA,IDRII,NDN1,0,SW,DATA)
 570  CONTINUE
      CALL PLOT (0.0,0.0,999)
      STOP
      END
```

```
      SUBROUTINE PLOTB (NP,MAX,BETA,FNCT,TIME,BU,BL,NZERO)
C
C  PLOTB USES THE PRINTER AS A PLOTTER.
C        NP = NUMBER OF FUNCTIONS PLOTTED ON THE GRAPH, MAXIMUM OF 10
C        MAX = NUMBER OF DATA POINTS IN EACH FUNCTION
C        BETA = SCALE OF THE Y AXIS (ABSCISSA) IN UNITS OF TIME
C        BU AND BL = THE UPPER AND LOWER LIMITS OF THE X AXIS (ORDINATE).
C                    IF BU=BL=0.0 THE THE MAXIMUM AND MINIMUM VALUES OF
C                    THE FUNCTION ARE USED AS THE LIMITS.
C        NZERO = 1  WILL PUT A REFERENCE LINE AT X=0.  IF A REFERENCE
C                LINE IS NOT DESIRED SET NZERO = 0.
C
      INTEGER BLANK, DASH, DOT, DOLAR, AM(10)
      DIMENSION KK(10), LINE(101)
      DIMENSION FNCT(5,500),TIME(500)
      DATA NPR /  6 /
      DATA BLANK,DASH,DOT,AM(1),AM(2),AM(3),AM(4),AM(5),AM(6),AM(7),    PLOT*
     1 AM(8),AM(9),AM(10) / ' ', '-', '.', '1', '2', '3', '4', '5',     PLOT*
     2 '6', '7', '8', '9', '0' /
      DATA DOLAR /  '$'  /
      IF (BU .EQ. 0.0  .AND.  BL .EQ. 0.0) GO TO 210
      BIG = BU
      SMALL = BL
      GO TO 507
 210  BIG=FNCT(1,1)
      SMALL=BIG
      DO  212   M =  1,  NP
      DO  212   L = 2, MAX
      IF (FNCT(M,L)-BIG) 260,260,213
  213 BIG=FNCT(M,L)
  260 IF (FNCT(M,L)-SMALL) 214,212,212
  214 SMALL=FNCT(M,L)
  212 CONTINUE
  507 PEAK=BIG-SMALL
      APEAK = ABS(PEAK)
      AMID=(BIG+SMALL)/2.0
```

```
      SCALE=APEAK/80.0
      WRITE (NPR,112) AMID, BIG, SMALL, SCALE
  112 FORMAT (1H1,4X,'1-CURVE ORDINATE',5X,'MID-VALUE=',
     2E10.3,21X,'MAX-VALUE=',E10.3,8X,'MIN-VALUE=',
     3E10.3,//,27X,'SCALE=',E10.3,2X,'PER LINE',//)
      WRITE (NPR,113) BETA
  113 FORMAT (1H ,4X,'ABSCISSA',13X,'SCALE=',
     2E10.3,2X,'PER LINE',62X,'W-RPS',//)
      IF ( APEAK .NE. 0.0 ) GOTO 35
      WRITE(NPR,30)
   30 FORMAT(1H0,4X,'**************************************************
     1**************'/15X,'NO PLOT WILL BE PRODUCED HERE BECAUSE'/15X,
     2'FUNCTION MAX VALUE = FUNCTION MIN VALUE.'/15X,'THE FUNCTION IS CO
     3NSTANT.  TO RECEIVE A '/15X,'PLOT OF THIS FUNCTION, PREDETERMINED'
     4/15X,'UPPER AND LOWER LIMITS BU AND BL MUST'/15X,'BE SPECIFIED.'/5
     5X,'**************************************************************
     6**')
      GOTO 41
   35 CONTINUE
      DO 38 I = 1,101
   39 LINE(I)=DASH
      LINE(11) = DOT
      LINE(51) = DOT
      LINE(91) = DOT
      DO 41 J = 1,MAX
      DO 40 K=1,NP
      KK(K)=80.0*(FNCT(K,J)-AMID)/APEAK + 51.0
      KKK = KK(K)
      IF(KKK) 51,51,52
   51 LINE(1) = DOLAR
      GO TO 54
  52  IF(KKK-101) 50,50,53
   53 LINE(101) = DOLAR
      GO TO 54
   50 LINE(KKK) = AM(K)
```

```
      GOTO 12
   11 CENTER=0.0
      LETTER=-1
   12 CONTINUE
      DO 4 KK=1,J
      KKK=KK+J
      YY(KK)=FUNCT(KK,1)
      YY(KKK)=FUNCT(KK,1)
      DO 5 L=1,JJ
      Y(L)=FUNCT(KK,L)
      IF (YY(KK).GT.Y(L))YY(KK)=Y(L)
      IF (YY(KKK).LT.Y(L)) YY(KKK)=Y(L)
    5 CONTINUE
    4 CONTINUE
      JJJ=2*J
      CALL SCALE (YY,SH,JJJ,K)
      CALL SCALE (TIME, SW, JJ, K)
C
C     X-SCALE OVERRIDE CAN BE DONE HERE BY SPECIFYING  TIME(JJ+1)  AS
C     THE VALUE OF THE FIRST TIC MARK ON THE X-AXIS AND  TIME(JJ+2)  AS
C     THE CHANGE IN X VALUE BETWEEN TWO TIC MARKS.
C
      CALL AXIS (0.0,CENTER,' ',LETTER,SW,0.0,TIME(JJ+1),TIME(JJ+2))
      CALL AXIS (0.0,0.0,' ',0,SH,90.0,YY(JJJ+1),YY(JJJ+2))
      DO 8 NP=1,J
      DO 9 LL=1,JPTS
      Y(LL)=FUNCT(NP, LL)
    9 CONTINUE
      Y(JJ+1)=YY(JJJ+1)
      Y(JJ+2)=YY(JJJ+2)
    2 CALL LINE (TIME, Y, JPTS, 1, 0, 0)
    8 CONTINUE
      CALL PLOT (SW+2.0, 0.0, -3)
      RETURN
      END
```

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```
54  CONTINUE
 40 CONTINUE
    IF ( NZERO .NE. 1 ) GOTO 44
    KKK = 80.0 * (-AMID)/APEAK + 51.0
    LINE(KKK) = AM(10)
44  CONTINUE
    WRITE (NPR, 39)  J, LINE, TIME(J)
 39 FORMAT (1H ,4X,I3,1X,101A1,1X,E10.3)
    DO 43 L = 1,101
 43 LINE(L) = BLANK
    LINE(1)=DOT
 41 CONTINUE
    WRITE (NPR, 442 )
442 FORMAT ( 1H , 26X,'****' ,  'PLOTTING ROUTINE COMPLETED', 12X, '***PLOT*
   1'     )
    RETURN
    END

      SUBROUTINE MCPLOT (FUNCT,TIME,JJ,J,NOMAG1,SW,DATA)
C     THIS SUBROUTINE PLOTS GRAPHS ON CALCOMP PLOTTER
C     VARIABLES ARE DEFINED AS FOLLOWS:
C            FUNCT= ARRAY OF Y VALUES
C            TIME= ARRAY OF X VALUES
C            J= NUMBER OF PLOTS PER GRAPH
C            JJ= NUMBER OF POINTS PER PLOT
C            SW= X AXIS LENGTH IN INCHES
C            SH= Y AXIS LENGTH IN INCHES
    DIMENSION FUNCT (5,500), TIME (500), Y(500), DATA (1024), YY(500)
    SW=10.1
    JPTS=JJ
    SH=7.5
    K=1
    IF (NOMAG1) 11, 11, 10
 10 CENTER=SH
    LETTER=0
```

```
      SUBROUTINE CALC(R,V,DT,X,IDI,RE,RDOT,K1,K2,RDI,RVI,L,RM,Y,IDRI)
C  FILTER 1    BLOCK DIAGRAM 1
      IMPLICIT REAL*8(D,K,R,V)
      DIMENSION X(50,5),Y(2500)
      IDRIST = IDRI - 50/IDI
      IDIST = IDI-50+(50/IDI)*IDI
      A=0.0
      DO 50 LAP=1,IDI
C  ACCELERATION CAN BE ADDED FOR A PERIOD OF 10*IDI*DT HERE, L=41 TO 50
      IF((L.GT.40).AND.(L.LE.50)) A=0.0
      V=V+A*DT
C  NEW RANGE, R (TRUE RANGE)
      R=R+V*DT
C  ADD RANDOM NO., RM (NOISY RANGE)
      RM = R + Y(LAP)
C  NOISY RANGE MINUS PREVIOUS ESTIMATED RANGE
      RV=RM-RE
C  ESTIMATED RANGE RATE, RDOT
      RDOT=RDOT+K2*RV*DT
C  ESTIMATED RANGE, RE
      RDI=RDI+RDOT*DT
      RVI=RVI+K1*RV*DT
      RE=RDI+RVI
      IF(L .LT. IDRIST) GOTO 50
      IF(L .EQ. IDRIST  .AND.  LAP .LE. IDIST) GOTO 50
      LAPX = (L-1)*IDI + LAP - ((IDRIST-1)*IDI + IDIST)
      X(LAPX,1) = RM
      X(LAPX,2) = RE
      X(LAPX,3) = RDOT
      X(LAPX,4) = RE-R
      X(LAPX,5) = RDOT-V
 50   CONTINUE
      RETURN
      END
```

```
      SUBROUTINE CALC(R,V,DT,X,IDI,RE,RDOT,K1,K2,RDI,RVI,L,RM,Y,IDRI)
C ALPHA-BETA FILTER
C BETA = ALPHA**2/(2-ALPHA)
      IMPLICIT REAL*8(D,K,R,V)
      DIMENSION X(50,5),Y(2500)
      IDRIST = IDRI - 50/IDI
      IDIST = IDI-50+(50/IDI)*IDI
      A=0.0
      DO 50 LAP=1,IDI
C  ACCELERATION CAN BE ADDED FOR A PERIOD OF 10*IDI*DT HERE, L=41 TO 50
      IF((L.GT.40).AND.(L.LE.50)) A=0.0
      V=V+A*DT
C  NEW RANGE, R (TRUE RANGE)
      R=R+V*DT
C  ADD RANDOM NO., RM (NOISY RANGE)
      RM = R  + Y(LAP)
      RE = RDI+K1*(RM-RDI)
      RDOT = RDOT+K2/DT*(RM-RDI)
      RDI = RE+DT*RDOT
      IF(L .LT. IDRIST) GOTO 50
      IF(L .EQ. IDRIST  .AND.  LAP .LE. IDIST) GOTO 50
      LAPX = (L-1)*IDI + LAP - ((IDRIST-1)*IDI + IDIST)
      X(LAPX,1) = RM
      X(LAPX,2) = RE
      X(LAPX,3) = RDOT
      X(LAPX,4) = RE-R
      X(LAPX,5) = RDOT-V
  50  CONTINUE
      RETURN
      END
```

```
      SUBROUTINE CALC(R,V,DT,X,IDI,RE,RDOT,K1,K2,RDI,RVI,L,RM,Y,IDRI)
C  FILTER 3                  SMOOTHER
      IMPLICIT REAL*8(D,K,R,V)
      DIMENSION X(50,5),REG(18),Y(2500)
      IF (L .GT. 1) GOTO 10
      DATA REG/18*0.0D0/
   10 CONTINUE
      IDRIST = IDRI - 50/IDI
      IDIST = IDI-50+(50/IDI)*IDI
      A=0.0
      DO 50 LAP=1,IDI
C  ACCELERATION CAN BE ADDED FOR A PERIOD OF 10*IDI*DT HERE, L=41 TO 50
      IF((L.GT.40).AND.(L.LE.50))A=0.0
      V=V+A*DT
C  NEW RANGE, R (TRUE RANGE)
      R=R+V*DT
C  ADD RANDOM NO., RM (NOISY RANGE)
      RM = R + Y(LAP)
      REG(18) = REG(17)
      REG(17) = REG(16)
      REG(16) = REG(15)
      REG(15) = REG(14)
      REG(14) = REG(13)
      REG(13) = REG(12)
      REG(12) = REG(11)
      REG(11) = REG(10)
      REG(10) = REG( 9)
      REG( 9) = REG( 8)
      REG( 8) = REG( 7)
      REG( 7) = REG( 6)
      REG( 6) = REG( 5)
      REG( 5) = REG( 4)
      REG( 4) = REG( 3)
      REG( 3) = REG( 2)
      REG( 2) = REG( 1)
```

```
      REG( 1) = RM
      DSUM = 0.0
      DO 30 I=1,6
      DSUM = DSUM + REG(I) - REG(I+12)
  30  CONTINUE
C  ESTIMATED RANGE RATE, RDOT
      RDOTT = DSUM * 4.5/(18.0 * DT)
      RDOT = RDOTT/18.0
      DSUM = 0.0
      DO 40 I=1,16
      DSUM = DSUM + REG(I)
  40  CONTINUE
C  ESTIMATED RANGE, RE
      RE = DSUM/16.0 + RDOT *DT *7.5
      IF(L .EQ. 1) RE = RM
      IF(L .EQ. 1) RDOT = V
      IF(L .LT. IDRIST) GOTO 50
      IF((L .EQ. IDRIST) .AND. (LAP .LE. IDIST)) GOTO 50
      LAPX = (L-1)*IDI + LAP - ((IDRIST-1)*IDI + IDIST)
      X(LAPX,1) = RM
      X(LAPX,2) = RE
      X(LAPX,3) = RDOT
      X(LAPX,4) = RE-R
      X(LAPX,5) = RDOT-V
  50  CONTINUE
      RETURN
      END
```

```
      SUBROUTINE CALC(R,V,DT,X,IDI,RE,RDOT,K1,K2,RDI,RVI,L,RM,Y,IDRI)
C  FILTER 4   DESIGN 1
      IMPLICIT REAL*8(D,K,R,V)
      DIMENSION X(50,5),REG(4),Y(2500)
      IF (L .GT. 1) GOTO 10
      DATA REG/4*0.0D0/
  10  CONTINUE
      IDRIST = IDRI - 50/IDI
      IDIST = IDI-50+(50/IDI)*IDI
      A=0.0
      DO 50 LAP=1,IDI
C  ACCELERATION CAN BE ADDED FOR A PERIOD OF 10*IDI*DT HERE, L=41 TO 50
      IF((L.GT.40).AND.(L.LE.50)) A=0.0
      V=V+A*DT
C  NEW RANGE, R (TRUE RANGE)
      R=R+V*DT
      RM = R + Y(LAP)
      REG( 4) = REG( 3)
      REG( 3) = REG( 2)
      REG( 2) = REG( 1)
      REG( 1) = RM-RE
      DELTA = (REG(1)+REG(2)+REG(3)+REG(4))/4.0
      RE = DELTA + RE
      RDOT = DELTA/DT
      IF(L .LT. IDRIST) GOTO 50
      IF(L .EQ. IDRIST  .AND.  LAP .LE. IDIST) GOTO 50
      LAPX = (L-1)*IDI + LAP - ((IDRIST-1)*IDI + IDIST)
      X(LAPX,1) = RM
      X(LAPX,2) = RE
      X(LAPX,3) = RDOT
      X(LAPX,4) = RE-R
      X(LAPX,5) = RDOT-V
  50  CONTINUE
      RETURN
      END
```

```
      SUBROUTINE CALC(R,V,DT,X,IDI,RE,RDOT,K1,K2,RDI,RVI,L,RM,Y,IDRI)
C  FILTER 5
C  FOR THIS FILTER, CALCULATIONS ARE MADE EVERY 16 SAMPLES.
C  THIS MEANS THAT FOR EVERY RUN THROUGH CALC IDI/16 VALUES ARE
C  DETERMINED RATHER THAN IDI VALUES.  TO ALLOW FOR THIS, IDI IS CHANGED
C  TO IDI/16.  THIS IS NECESSARY  BECAUSE ALL THE VALUES CALCULATED
C  IN THE LAST RUN THROUGH CALC ARE RETURNED TO BE USED IN VARIANCE
C  CALCULATIONS.
C
C  *NOTE* - THE IMPLICATION OF THIS CHANGE IS THAT IDI MUST BE AN
C  INTEGRAL MULTIPLE OF 16.  ALSO, IDRI*IDI/16 MUST BE GREATER THAN 50.
C  THESE LIMITATIONS APPLY FOR FILTER 5 ONLY.
C
      IMPLICIT REAL*8(D,K,R,V)
      DIMENSION X(50,5),REG(16),Y(2500)
      IF (L .GT. 1) GOTO 10
      DATA REG/16*0.0D0/
   10 CONTINUE
      IDRIST = IDRI - (50/(IDI/16))
      IDIST = IDI-((50-(50/(IDI/16))*(IDI/16))*16)
      A=0.0
      DO 50 LAP=1,IDI
C  ACCELERATION CAN BE ADDED FOR A PERIOD OF 10*IDI*DT HERE, L=41 TO 50
      IF((L.GT.40).AND.(L.LE.50))A=0.0
      V=V+A*DT
C  NEW RANGE, R (TRUE RANGE)
      R=R+V*DT
C  ADD RANDOM NO., RM (NOISY RANGE)
      RM = R + Y(LAP)
      REG(16) = REG(15)
      REG(15) = REG(14)
      REG(14) = REG(13)
      REG(13) = REG(12)
      REG(12) = REG(11)
      REG(11) = REG(10)
```

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```
      REG(10) = REG( 9)
      REG( 9) = REG( 8)
      REG( 8) = REG( 7)
      REG( 7) = REG( 6)
      REG( 6) = REG( 5)
      REG( 5) = REG( 4)
      REG( 4) = REG( 3)
      REG( 3) = REG( 2)
      REG( 2) = REG( 1)
      REG( 1) = RM-RDI
      IF((LAP-(LAP/16)*16) .NE. 0) GOTO 50
      DSUM = 0.0
      DO 20 I=1,16
      DSUM = DSUM + REG(I)
   20 CONTINUE
      RDOT = DSUM/16.0/DT/16.0
      RDI = RDI + DSUM/16.0
      RE = RDI + DSUM/16.0*7.5/16.0
      IF(L .EQ. 1) RE = RM
      IF(L .EQ. 1) RDOT = V
      IF(L .LT. IDRIST) GOTO 50
      IF(L .EQ. IDRIST  .AND.  LAP .LE. IDIST) GOTO 50
      LAPX = ((L-1)*IDI + LAP - ((IDRIST-1)*IDI + IDIST))/16
      X(LAPX,1) = RM
      X(LAPX,2) = RE
      X(LAPX,3) = RDOT
      X(LAPX,4) = RE-R
      X(LAPX,5) = RDOT-V
   50 CONTINUE
      RETURN
      END
```

APPENDIX B

The following pages contain an assembly language listing of program FILTER 3.

```
                  *
                  *
                  *
                  *
                  * FILTER 3
                  *
0000                      ORG    $0000
0000              XTEMP   RMB    2
0002              SGN     RMB    1
0003              CNT     RMB    1
0004              MLTCD1  RMB    1
0005              MLTCD2  RMB    1
0006              MLTPR1  RMB    1
0007              MLTPR2  RMB    1
0008              MLTPR3  RMB    1
0009              PROD1   RMB    1
000A              PROD2   RMB    1
000B              PROD3   RMB    1
000C              PROD4   RMB    1
000D              PROD5   RMB    1
000E              A1      RMB    1
000F              A2      RMB    1
0010              A3      RMB    1
0011              B1      RMB    1
0012              B2      RMB    1
0013              B3      RMB    1
0014              SUM1    RMB    1
0015              SUM2    RMB    1
0016              SUM3    RMB    1
001E                      ORG    $001E
001E              RTEMP   RMB    2
0020              REGS    RMB    36
0044                      ORG    $0044
0044              RCNT    RMB    1
0045              SKPFLG  RMB    1
0046              RCRCT1  RMB    1
0047              RCRCT2  RMB    1
0048              RCRCT3  RMB    1
0049              RCRCT4  RMB    1
004A              ROOT1   RMB    1
004B              ROOT2   RMB    1
004C              RE1     RMB    1
004D              RE2     RMB    1
004E              TSUM1   RMB    1
004F              TSUM2   RMB    1
0050              TSUM3   RMB    1
0051              SAMP    RMB    2
0053              RAMPTR  RMB    2
0055              DATPTR  RMB    2
```

```
FILTER 3                                      DECEMBER 19, 1978

0057                REPTR     RMB    2
0059                RDOTPT    RMB    2
005B                SAMPND    RMB    2
005D                DIGIT     RMB    1
005E                TYPE      RMB    1
005F                ROUND     RMB    1
0060                NFLAG     RMB    1
0061                C1        RMB    1
0062                C2        RMB    1
0063                D1        RMB    1
0064                D2        RMB    1
0065                DIFF1     RMB    1
0066                DIFF2     RMB    1
                    *
                    *
0200                          ORG    $0200
0200 C6 01          FLT       LDA B  #$01
0202 D7 5F                    STA B  ROUND
0204 CE 00 01                 LDX    #$0001
0207 DF 51                    STX    SAMP
0209 CE 30 00                 LDX    #$3000
020C DF 57                    STX    REPTR
020E CE 38 00                 LDX    #$3800
0211 DF 59                    STX    RDOTPT
0213 CE 04 3C                 LDX    #INIT1
0216 BD E1 4B                 JSR    $E14B         MINIBUG PDATA1
0219 BD E1 33                 JSR    $E133         MINIBUG INCH
021C 97 5E                    STA A  TYPE
021E 44                       LSR A
021F 24 05                    BCC    INPUT1
0221 CE 20 00                 LDX    #$2000
0224 20 0B                    BRA    INPUT3
0226 44             INPUT1    LSR A
0227 24 05                    BCC    INPUT2
0229 CE 28 00                 LDX    #$2800
022C 20 03                    BRA    INPUT3
022E CE 18 00       INPUT2    LDX    #$1800
0231 DF 55          INPUT3    STX    DATPTR
0233 CE 04 9E                 LDX    #INIT2
0236 BD E1 4B                 JSR    $E14B         MINIBUG PDATA1
0239 BD E0 F8                 JSR    $E0F8         MINIBUG BADDR
023C DF 5B                    STX    SAMPND
023E CE 00 20                 LDX    #REGS
0241 6F 00          FLTA      CLR    0,X
0243 08                       INX
0244 8C 00 44                 CPX    #RCNT
0247 26 F9                    BNE    FLTA
0249 DE 55          FLT1      LDX    DATPTR
024B EE 00                    LDX    0,X
```

```
0240 BD 04 2C               JSR     SHFTR
0250 7F 00 14               CLR     SUM1
0253 7F 00 15               CLR     SUM2
0256 7F 00 16               CLR     SUM3
0259 CE 00 20               LDX     #REGS
025C C6 06                  LDA B   #$06
025E D7 44                  STA B   RCNT
0260 7F 00 45               CLR     SKPFLG
0263 DF 00         FLT2     STX     XTEMP
0265 CE 00 0E               LDX     #A1
0268 A6 06         FLT3     LDA A   6,X
026A A7 00                  STA A   0,X
026C 08                     INX
026D 8C 00 11               CPX     #B1
0270 26 F6                  BNE     FLT3
0272 DE 00                  LDX     XTEMP
0274 8C 00 2C               CPX     #$002C
0277 26 03                  BNE     FLT4
0279 7A 00 45               DEC     SKPFLG
027C 8C 00 38      FLT4     CPX     #$0038
027F 26 03                  BNE     FLT5
0281 7F 00 45               CLR     SKPFLG
0284 D6 45         FLT5     LDA B   SKPFLG
0286 26 18                  BNE     FLT7
0288 7F 00 11               CLR     B1
028B A6 00                  LDA A   0,X
028D E6 01                  LDA B   1,X
028F 97 12                  STA A   B2
0291 D7 13                  STA B   B3
0293 7A 00 44               DEC     RCNT
0296 2A 05                  BPL     FLT6
0298 BD 04 19               JSR     SUB
029B 20 03                  BRA     FLT7
029D BD 04 06      FLT6     JSR     ADD
02A0 08            FLT7     INX
02A1 08                     INX
02A2 8C 00 44               CPX     #RCNT
02A5 26 BC                  BNE     FLT2
02A7 96 14                  LDA A   SUM1
02A9 97 4E                  STA A   TSUM1
02AB 97 06                  STA A   MLTPR1
02AD DE 15                  LDX     SUM2
02AF DF 4F                  STX     TSUM2
02B1 DF 07                  STX     MLTPR2
02B3 CE 1A AB               LDX     #$1AAB
02B6 DF 04                  STX     MLTCD1
02B8 7F 00 5F               CLR     ROUND
02BB BD 03 64               JSR     MULT
02BE DE 0A                  LDX     PROD2
```

```
02C0 DF 46                  STX     RCRCT1
02C2 DE 0C                  LDX     PROD4
02C4 DF 48                  STX     RCRCT3
02C6 D6 4E                  LDA B   TSUM1
02C8 D7 06                  STA B   MLTPR1
02CA DE 4F                  LDX     TSUM2
02CC DF 07                  STX     MLTPR2
02CE CE 16 39               LDX     #$1639
02D1 DF 04                  STX     MLTCD1
02D3 7C 00 5F               INC     ROUND
02D6 BD 03 64               JSR     MULT
02D9 DE 0A                  LDX     PROD2
02DB DF 4A                  STX     RDOT1
02DD 7F 00 14               CLR     SUM1
02E0 7F 00 15               CLR     SUM2
02E3 7F 00 16               CLR     SUM3
02E6 CE 00 20               LDX     #REGS
02E9 DF 00         FLT10    STX     XTEMP
02EB CE 00 0E               LDX     #A1
02EE A6 06         FLT12    LDA A   6,X
02F0 A7 00                  STA A   0,X
02F2 08                     INX
02F3 8C 00 11               CPX     #B1
02F6 26 F6                  BNE     FLT12
02F8 DE 00                  LDX     XTEMP
02FA 7F 00 11               CLR     B1
02FD EE 00                  LDX     0,X
02FF DF 12                  STX     B2
0301 BD 04 06               JSR     ADD
0304 DE 00                  LDX     XTEMP
0306 08                     INX
0307 08                     INX
0308 8C 00 40               CPX     #$0040
030B 26 DC                  BNE     FLT10
030D D6 14                  LDA B   SUM1
030F D7 06                  STA B   MLTPR1
0311 DE 15                  LDX     SUM2
0313 DF 07                  STX     MLTPR2
0315 CE 10 00               LDX     #$1000
0318 DF 04                  STX     MLTCD1
031A 7F 00 5F               CLR     ROUND
031D BD 03 64               JSR     MULT
0320 DE 46                  LDX     RCRCT1
0322 08                     INX
0323 D6 49                  LDA B   RCRCT4
0325 96 48                  LDA A   RCRCT3
0327 DB 0D                  ADD B   PROD5
0329 99 0C                  ADC A   PROD4
032B 2A 02                  BPL     FLT14
```

```
032D DF 46               STX     RCRCT1
032F D6 47      FLT14    LDA B   RCRCT2
0331 96 46               LDA A   RCRCT1
0333 D9 0B               ADC B   PROD3
0335 99 0A               ADC A   PROD2
0337 DE 57      OUT      LDX     REPTR
0339 A7 00               STA A   0,X
033B E7 01               STA B   1,X
033D 08                  INX
033E 08                  INX
033F DF 57               STX     REPTR
0341 DE 59      OUT1     LDX     RDOTPT
0343 96 4A               LDA A   RDOT1
0345 D6 4B               LDA B   RDOT2
0347 A7 00               STA A   0,X
0349 E7 01               STA B   1,X
034B 08                  INX
034C 08                  INX
034D DF 59               STX     RDOTPT
034F DE 55               LDX     DATPTR
0351 08                  INX
0352 08                  INX
0353 DF 55               STX     DATPTR
0355 DE 51               LDX     SAMP
0357 9C 5B               CPX     SAMPND
0359 27 06               BEQ     END
035B 08                  INX
035C DF 51               STX     SAMP
035E 7E 02 49            JMP     FLT1
0361 7E 04 E4   END      JMP     PRINTR
                *
                *  3 BYTE X 2 BYTE 2'S COMPLEMENT MULTIPLY
                *
0364 DF 00      MULT     STX     XTEMP
0366 CE 00 02            LDX     #SGN
0369 6F 00               CLR     0,X
036B 6C 00               INC     0,X
036D A6 02               LDA A   2,X
036F 2A 0B               BPL     MULT1
0371 E6 03               LDA B   3,X
0373 BD 03 FE            JSR     NEGATE
0376 A7 02               STA A   2,X
0378 E7 03               STA B   3,X
037A 6A 00               DEC     0,X
037C A6 04      MULT1    LDA A   4,X
037E 2A 14               BPL     MULT2
0380 A6 05               LDA A   5,X
0382 E6 06               LDA B   6,X
0384 BD 03 FE            JSR     NEGATE
```

```
0387 A7 05                STA A  5,X
0389 E7 06                STA B  6,X
038B A6 04                LDA A  4,X
038D BD 03 FF             JSR    NEG4
0390 A7 04                STA A  4,X
0392 6A 00                DEC    0,X
0394 86 E7       MULT2    LDA A  #$E7
0396 A7 01                STA A  1,X
0398 4F                   CLR A
0399 5F                   CLR B
039A 6C 01       MULT3    INC    1,X
039C 27 16                BEQ    MULT4
039E 64 04                LSR    4,X
03A0 66 05                ROR    5,X
03A2 66 06                ROR    6,X
03A4 24 04                BCC    MULT31
03A6 EB 03                ADD B  3,X
03A8 A9 02                ADC A  2,X
03AA 44          MULT31   LSR A
03AB 56                   ROR B
03AC 66 09                ROR    9,X
03AE 66 0A                ROR    10,X
03B0 66 0B                ROR    11,X
03B2 20 E6                BRA    MULT3
03B4 A7 07       MULT4    STA A  7,X
03B6 E7 08                STA B  8,X
03B8 7D 00 5F    ROUND1   TST    ROUND
03BB 27 18                BEQ    MULT5
03BD 7D 00 0C             TST    PROD4
03C0 2A 0D                BPL    ROUND2
03C2 7C 00 0B             INC    PROD3
03C5 26 08                BNE    ROUND2
03C7 7C 00 0A             INC    PROD2
03CA 26 03                BNE    ROUND2
03CC 7C 00 09             INC    PROD1
03CF 7F 00 0C    ROUND2   CLR    PROD4
03D2 7F 00 0D             CLR    PROD5
03D5 66 00       MULT5    ROR    0,X
03D7 25 1D                BCS    MULTND
03D9 A6 0A                LDA A  10,X
03DB E6 0B                LDA B  11,X
03DD BD 03 FE             JSR    NEGATE
03E0 A7 0A                STA A  10,X
03E2 E7 0B                STA B  11,X
03E4 A6 08                LDA A  8,X
03E6 E6 09                LDA B  9,X
03E8 BD 03 F9             JSR    NEG3
03EB A7 08                STA A  8,X
03ED E7 09                STA B  9,X
```

```
03EF A6 07                LDA A  7,X
03F1 BD 03 FF             JSR    NEG4
03F4 A7 07                STA A  7,X
03F6 DE 00       MULTND   LDX    XTEMP
03F8 39                   RTS
                 ◆
                 ◆ 2'S COMPLEMENT ROUTINE
                 ◆
03F9 24 03       NEG3     BCC    NEGATE
03FB 53                   COM B
03FC 20 06                BRA    NEG1
03FE 50          NEGATE   NEG B
03FF 25 03       NEG4     BCS    NEG1
0401 40                   NEG A
0402 20 01                BRA    NEG2
0404 43          NEG1     COM A
0405 39          NEG2     RTS
                 ◆
                 ◆ 3 BYTE ADDITION ROUTINE
                 ◆
0406 D6 10       ADD      LDA B  A3
0408 96 0F                LDA A  A2
040A DB 13                ADD B  B3
040C 99 12                ADC A  B2
040E D7 16                STA B  SUM3
0410 97 15                STA A  SUM2
0412 96 0E                LDA A  A1
0414 99 11                ADC A  B1
0416 97 14                STA A  SUM1
0418 39                   RTS
                 ◆
                 ◆ 3 BYTE SUBTRACTION ROUTINE
                 ◆
0419 D6 10       SUB      LDA B  A3
041B 96 0F                LDA A  A2
041D D0 13                SUB B  B3
041F 92 12                SBC A  B2
0421 D7 16                STA B  SUM3
0423 97 15                STA A  SUM2
0425 96 0E                LDA A  A1
0427 92 11                SBC A  B1
0429 97 14                STA A  SUM1
042B 39                   RTS
                 ◆
                 ◆ ROUTINE TO SHIFT DATA IN REGS
                 ◆
042C DF 1E       SHFTR    STX    RTEMP
042E CE 00 41             LDX    #$0041
0431 E6 00       SHFTR1   LDA B  0,X
```

```
0433 E7 02                 STA B  2,X
0435 09                    DEX
0436 8C 00 1D              CPX    #$001D
0439 26 F6                 BNE    SHFTR1
043B 39                    RTS

043C 0D           INIT1    FCB    $D,$A,$A,$A,$A,$A,$A
043D 0A 0A
043F 0A 0A
0441 0A 0A
0443 46                    FCC    /FILTER 3 MICROPROCESSOR/
0444 49 4C
0446 54 45
0448 52 20
044A 33 20
044C 4D 49
044E 43 52
0450 4F 50
0452 52 4F
0454 43 45
0456 53 53
0458 4F 52
045A 20                    FCC    / SIMULATION RUN/
045B 53 49
045D 4D 55
045F 4C 41
0461 54 49
0463 4F 4E
0465 20 52
0467 55 4E
0469 0D                    FCB    $D,$A,$A
046A 0A 0A
046C 49                    FCC    /INPUT CHOICE?/
046D 4E 50
046F 55 54
0471 20 43
0473 48 4F
0475 49 43
0477 45 3F
0479 0D                    FCB    $D,$A
047A 0A
047B 28                    FCC    /(SIGNAL=0,NOISE=1,/
047C 53 49
047E 47 4E
0480 41 4C
0482 3D 30
0484 2C 4E
0486 4F 49
0488 53 45
```

```
 048A 3D 31
 048C 2C
 048D 53                   FCC     /SIGNAL+NOISE=2) /
 048E 49 47
 0490 4E 41
 0492 4C 2B
 0494 4E 4F
 0496 49 53
 0498 45 3D
 049A 32 29
 049C 20
 049D 04                   FCB     04
 049E 0D           INIT2   FCB     $D,$A,$A
 049F 0A 0A
 04A1 4E                   FCC     /NUMBER OF /
 04A2 55 4D
 04A4 42 45
 04A6 52 20
 04A8 4F 46
 04AA 20
 04AB 53                   FCC     /SAMPLES TO BE RUN?/
 04AC 41 4D
 04AE 50 4C
 04B0 45 53
 04B2 20 54
 04B4 4F 20
 04B6 42 45
 04B8 20 52
 04BA 55 4E
 04BC 3F
 04BD 0D                   FCB     $D,$A
 04BE 0A
 04BF 28                   FCC     /(ENTER A 4 DIGIT /
 04C0 45 4E
 04C2 54 45
 04C4 52 20
 04C6 41 20
 04C8 34 20
 04CA 44 49
 04CC 47 49
 04CE 54 20
 04D0 48                   FCC     /HEXIDECIMAL VALUE) /
 04D1 45 53
 04D3 49 44
 04D5 45 43
 04D7 49 40
 04D9 41 4C
 04DB 20 56
 04DD 41 4C
```

```
04DF 55 45
04E1 29 20
04E3 04                 FCB     04
                *
                *
                *
                *  FILTER DATA PRINTER PROGRAM
                *
04E4 CE 00 01   PRINTR  LDX     #$0001
04E7 DF 51              STX     SAMP
04E9 CE 18 00           LDX     #$1800
04EC DF 53              STX     RAMPTR
04EE CE 30 00           LDX     #$3000
04F1 DF 57              STX     REPTR
04F3 CE 38 00           LDX     #$3800
04F6 DF 59              STX     RDOTPT
04F8 CE 06 18           LDX     #HEAD1
04FB BD E1 4B           JSR     $E14B     MINIBUG PDATA1
04FE 96 5E              LDA A   TYPE
0500 44                 LSR A
0501 24 0B              BCC     PRINT1
0503 CE 06 43           LDX     #NHEAD
0506 BD E1 4B           JSR     $E14B     MINIBUG PDATA1
0509 CE 20 00           LDX     #$2000
050C 20 17              BRA     PRINT3
050E 44         PRINT1  LSR A
050F 24 0B              BCC     PRINT2
0511 CE 06 4E           LDX     #RNHEAD
0514 BD E1 4B           JSR     $E14B     MINIBUG PDATA1
0517 CE 28 00           LDX     #$2800
051A 20 09              BRA     PRINT3
051C CE 06 38   PRINT2  LDX     #RHEAD
051F BD E1 4B           JSR     $E14B     MINBUG PDATA1
0522 CE 18 00           LDX     #$1800
0525 DF 55      PRINT3  STX     DATPTR
0527 CE 06 59           LDX     #HEAD2
052A BD E1 4B           JSR     $E14B     MINIBUG PDATA1
052D C6 05              LDA B   #$05
052F CE 06 74           LDX     #HEAD4
0532 20 09              BRA     PRINT5
0534 CE 06 80   PRINT4  LDX     #HEAD5
0537 BD E1 4B           JSR     $E14B     MINIBUG PDATA1
053A CE 06 73           LDX     #HEAD3
053D BD E1 4B   PRINT5  JSR     $E14B     MINBUG PDATA1
0540 5A                 DEC B
0541 26 F1              BNE     PRINT4
0543 CE 06 82   LOOP    LDX     #HEAD6
0546 BD E1 4B           JSR     $E14B     MINIBUG PDATA1
0549 CE 00 51           LDX     #SAMP
```

```
FILTER 3                                 DECEMBER 19, 1978

 054C DF 00                STX    XTEMP
 054E 20 2D                BRA    LOOP5
 0550 CE 06 8C  LOOP1      LDX    #HEAD7
 0553 BD E1 4B             JSR    $E14B     MINIBUG PDATA1
 0556 DE 00                LDX    XTEMP
 0558 8C 00 59             CPX    #RDOTPT
 055B 26 1E                BNE    LOOP3
 055D 86 20                LDA A  #$20
 055F BD E1 26             JSR    $E126     OUTCH
 0562 EE 00                LDX    0,X
 0564 E6 01                LDA B  1,X
 0566 A6 00                LDA A  0,X
 0568 2A 0B                BPL    LOOP2
 056A 36                   PSH A
 056B CE 06 95             LDX    #MINUS
 056E BD E1 4B             JSR    $E14B     MINIBUG PDATA1
 0571 32                   PUL A
 0572 BD 03 FE             JSR    NEGATE
 0575 97 61     LOOP2      STA A  C1
 0577 D7 62                STA B  C2
 0579 20 06                BRA    LOOP4
 057B EE 00     LOOP3      LDX    0,X
 057D EE 00     LOOP5      LDX    0,X
 057F DF 61                STX    C1
 0581 BD 05 BD  LOOP4      JSR    CONV
 0584 DE 00                LDX    XTEMP
 0586 08                   INX
 0587 08                   INX
 0588 DF 00                STX    XTEMP
 058A 8C 00 5B             CPX    #SAMPND
 058D 26 C1                BNE    LOOP1
 058F DE 53                LDX    RAMPTR
 0591 08                   INX
 0592 08                   INX
 0593 DF 53                STX    RAMPTR
 0595 DE 55                LDX    DATPTR
 0597 08                   INX
 0598 08                   INX
 0599 DF 55                STX    DATPTR
 059B DE 57                LDX    REPTR
 059D 08                   INX
 059E 08                   INX
 059F DF 57                STX    REPTR
 05A1 DE 59                LDX    RDOTPT
 05A3 08                   INX
 05A4 08                   INX
 05A5 DF 59                STX    RDOTPT
 05A7 DE 51                LDX    SAMP
 05A9 9C 5B                CPX    SAMPND
```

```
05AB 27 05                BEQ     PEND
05AD 08                   INX
05AE DF 51                STX     SAMP
05B0 20 91                BRA     LOOP
05B2 86 0A       PEND     LDA A   #$0A
05B4 C6 05                LDA B   #$05
05B6 BD E1 26    PEND1    JSR     $E126       MINIBUG OUTCH
05B9 5A                   DEC B
05BA 26 FA                BNE     PEND1
05BC 3F                   SWI
                 *
                 *
05BD 7F 00 60    CONV     CLR     NFLAG
05C0 7D 00 61             TST     C1
05C3 2A 03                BPL     CONV1
05C5 7A 00 60             DEC     NFLAG
05C8 CE 27 10    CONV1    LDX     #$2710      10,000
05CB BD 05 E8             JSR     FACTOR
05CE CE 03 E8             LDX     #$03E8      1,000
05D1 BD 05 E8             JSR     FACTOR
05D4 CE 00 64             LDX     #$0064      100
05D7 BD 05 E8             JSR     FACTOR
05DA CE 00 0A             LDX     #$000A      10
05DD BD 05 E8             JSR     FACTOR
05E0 96 62                LDA A   C2
05E2 8A 30                ORA A   #$30
05E4 BD E1 26             JSR     $E126       MINIBUG OUTCH
05E7 39                   RTS
                 *
                 *
05E8 DF 63       FACTOR   STX     D1
05EA 7F 00 5D             CLR     DIGIT
05ED BD 06 0B    FACT     JSR     SUB2BY
05F0 2B 0C                BMI     FACTND
05F2 7F 00 60             CLR     NFLAG
05F5 7C 00 5D    FACT1    INC     DIGIT
05F8 DE 65                LDX     DIFF1
05FA DF 61                STX     C1
05FC 20 EF                BRA     FACT
05FE 7D 00 60    FACTND   TST     NFLAG
0601 2B F2                BMI     FACT1
0603 96 5D                LDA A   DIGIT
0605 8A 30                ORA A   #$30
0607 BD E1 26             JSR     $E126
060A 39                   RTS
                 *
                 *   2 BYTE SYBTRACTION ROUTINE
                 *
060B D6 62       SUB2BY   LDA B   C2
```

```
060D 96 61                   LDA A  C1
060F D0 64                   SUB B  D2
0611 92 63                   SBC A  D1
0613 D7 66                   STA B  DIFF2
0615 97 65                   STA A  DIFF1
0617 39                      RTS
                 *
                 *
0618 0D          HEAD1       FCB    $0D,$0A,$0A,$0A,$0A
0619 0A 0A
061B 0A 0A
061D 20                      FCC    / SAMPLE    !     RAMP    ! /
061E 53 41
0620 4D 50
0622 4C 45
0624 20 20
0626 20 20
0628 21 20
062A 20 20
062C 20 52
062E 41 4D
0630 50 20
0632 20 20
0634 20 21
0636 20
0637 04                      FCB    $04
0638 20          RHEAD       FCC    /   RAMP   /
0639 20 20
063B 52 41
063D 4D 50
063F 20 20
0641 20
0642 04                      FCB    $04
0643 20          NHEAD       FCC    /   NOISE  /
0644 20 20
0646 4E 4F
0648 49 53
064A 45 20
064C 20
064D 04                      FCB    $04
064E 52          RNHEAD      FCC    /RAMP+NOISE/
064F 41 4D
0651 50 2B
0653 4E 4F
0655 49 53
0657 45
0658 04                      FCB    $04
0659 20          HEAD2       FCC    / !      RE      !     RDOT/
065A 21 20
```

```
 0650 20 20
 065E 20 20
 0660 52 45
 0662 20 20
 0664 20 20
 0666 20 21
 0668 20 20
 066A 20 20
 066C 52 44
 066E 4F 54
 0670 0D           HEAD8    FCB    $0D,$0A,$04
 0671 0A 04
 0673 2D           HEAD3    FCC    /-/
 0674 2D           HEAD4    FCC    /-----------/
 0675 2D 2D
 0677 2D 2D
 0679 2D 2D
 067B 2D 2D
 067D 2D 2D
 067F 04                    FCB    $04
 0680 21           HEAD5    FCB    $21,$04
 0681 04
 0682 00 0D        HEAD6    FDB    $0D,$0A,$20,$20,$04
 0684 00 0A
 0686 00 20
 0688 00 20
 068A 00 04
 068C 20           HEAD7    FCC    /    !    /
 068D 20 20
 068F 20 21
 0691 20 20
 0693 20
 0694 04                    FCB    $04
 0695 08           MINUS    FCB    $08,$2D,$04
 0696 2D 04
                            END
       NO ERROR(S) DETECTED


   SYMBOL TABLE:
A1        000E          A2        000F          A3        0010
ADD       0406          B1        0011          B2        0012
B3        0013          C1        0061          C2        0062
CNT       0003          CONV      05BD          CONV1     05C8
D1        0063          D2        0064          DATPTR    0055
DIFF1     0065          DIFF2     0066          DIGIT     005D
END       0361          FACT      05ED          FACT1     05F5
FACTND    05FE          FACTOR    05E8          FLT       0200
```

```
FILTER 3                                         DECEMBER 19, 1978

FLT1      0249          FLT10     02E9          FLT12     02EE
FLT14     032F          FLT2      0263          FLT3      0268
FLT4      027C          FLT5      0284          FLT6      029D
FLT7      02A0          FLTA      0241          HEAD1     0618
HEAD2     0659          HEAD3     0673          HEAD4     0674
HEAD5     0680          HEAD6     0682          HEAD7     068C
HEAD8     0670          INIT1     043C          INIT2     049E
INPUT1    0226          INPUT2    022E          INPUT3    0231
LOOP      0543          LOOP1     0550          LOOP2     0575
LOOP3     057B          LOOP4     0581          LOOP5     057D
MINUS     0695          MLTCD1    0004          MLTCD2    0005
MLTPR1    0006          MLTPR2    0007          MLTPR3    0008
MULT      0364          MULT1     037C          MULT2     0394
MULT3     039A          MULT31    03AA          MULT4     03B4
MULT5     03D5          MULTND    03F6          NEG1      0404
NEG2      0405          NEG3      03F9          NEG4      03FF
NEGATE    03FE          NFLAG     0060          NHEAD     0643
OUT       0337          OUT1      0341          PEND      05B2
PEND1     05B6          PRINT1    050E          PRINT2    051C
PRINT3    0525          PRINT4    0534          PRINT5    053D
PRINTR    04E4          PROD1     0009          PROD2     000A
PROD3     000B          PROD4     000C          PROD5     000D
RAMPTR    0053          RCNT      0044          RCRCT1    0046
RCRCT2    0047          RCRCT3    0048          RCRCT4    0049
RDOT1     004A          RDOT2     004B          RDOTPT    0059
RE1       004C          RE2       004D          REGS      0020
REPTR     0057          RHEAD     0638          RNHEAD    064E
ROUND     005F          ROUND1    03B8          ROUND2    03CF
RTEMP     001E          SAMP      0051          SAMPND    005B
SGN       0002          SHFTR     042C          SHFTR1    0431
SKPFLG    0045          SUB       0419          SUB2BY    060B
SUM1      0014          SUM2      0015          SUM3      0016
TSUM1     004E          TSUM2     004F          TSUM3     0050
TYPE      005E          XTEMP     0000
```

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APPENDIX C

The following pages contain an assembly language listing of program FILTER 5.

```
                   *
                   *
                   *
                   * FILTER 5
                   *
0000                        ORG     $0000
0000               XTEMP    RMB     2
0002               SGN      RMB     1
0003               CNT      RMB     1
0004               MLTCD1   RMB     1
0005               MLTCD2   RMB     1
0006               MLTPR1   RMB     1
0007               MLTPR2   RMB     1
0008               MLTPR3   RMB     1
0009               PROD1    RMB     1
000A               PROD2    RMB     1
000B               PROD3    RMB     1
000C               PROD4    RMB     1
000D               PROD5    RMB     1
000E               A1       RMB     1
000F               A2       RMB     1
0010               A3       RMB     1
0011               B1       RMB     1
0012               B2       RMB     1
0013               B3       RMB     1
0014               SUM1     RMB     1
0015               SUM2     RMB     1
0016               SUM3     RMB     1
001E                        ORG     $001E
001E               RTEMP    RMB     2
0020               REGS     RMB     32
0040               REGSND   RMB     4
0044                        ORG     $0044
0044               RCNT     RMB     1
0045               SKPFLG   RMB     1
0046               RCRCT1   RMB     1
0047               RCRCT2   RMB     1
0048               RDOT1    RMB     1
0049               RDOT2    RMB     1
004A               RE1      RMB     1
004B               RE2      RMB     1
004C               TSUM1    RMB     1
004D               TSUM2    RMB     1
004E               TSUM3    RMB     1
004F               SAMP     RMB     2
0051               RAMPTR   RMB     2
0053               DATPTR   RMB     2
0055               REPTR    RMB     2
0057               RDOTPT   RMB     2
```

```
0059                SAMPND   RMB     2
005B                DIGIT    RMB     1
005C                TYPE     RMB     1
005D                ROUND    RMB     1
005E                NFLAG    RMB     1
005F                C1       RMB     1
0060                C2       RMB     1
0061                D1       RMB     1
0062                D2       RMB     1
0063                DIFF1    RMB     1
0064                DIFF2    RMB     1
0065                RDI      RMB     2
0067                ENDFLG   RMB     1
                    *
                    *
0200                         ORG     $0200
0200 C6 01          FLT      LDA B   #$01
0202 D7 5D                   STA B   ROUND
0204 CE 00 01                LDX     #$0001
0207 DF 4F                   STX     SAMP
0209 CE 30 00                LDX     #$3000
020C DF 55                   STX     REPTR
020E CE 38 00                LDX     #$3800
0211 DF 57                   STX     RDOTPT
0213 CE 04 1F                LDX     #INIT1
0216 BD E1 4B                JSR     $E14B        MINIBUG PDATA1
0219 BD E1 33                JSR     $E133        MINIBUG INCH
021C 97 5C                   STA A   TYPE
021E 44                      LSR A
021F 24 05                   BCC     INPUT1
0221 CE 20 00                LDX     #$2000
0224 20 0B                   BRA     INPUT3
0226 44             INPUT1   LSR A
0227 24 05                   BCC     INPUT2
0229 CE 28 00                LDX     #$2800
022C 20 03                   BRA     INPUT3
022E CE 18 00       INPUT2   LDX     #$1800
0231 DF 53          INPUT3   STX     DATPTR
0233 CE 04 81                LDX     #INIT2
0236 BD E1 4B                JSR     $E14B        MINIBUG PDATA1
0239 BD E0 F8                JSR     $E0F8        MINIBUG BADDR
023C DF 59                   STX     SAMPND
023E CE 00 20                LDX     #REGS
0241 6F 00          FLTA     CLR     0,X
0243 08                      INX
0244 8C 00 44                CPX     #RCNT
0247 26 F8                   BNE     FLTA
0249 7F 00 67                CLR     ENDFLG
024C C6 10                   LDA B   #$10
```

```
 024E D7 44                   STA B   RCNT
 0250 DE 53                   LDX     DATPTR
 0252 EE 00                   LDX     0,X
 0254 DF 65                   STX     RDI
 0256 DE 53          FLT1     LDX     DATPTR
 0258 EE 00                   LDX     0,X
 025A DF 0F                   STX     A2
 025C DE 65                   LDX     RDI
 025E DF 12                   STX     B2
 0260 7F 00 0E                CLR     A1
 0263 7F 00 11                CLR     B1
 0266 BD 03 FC                JSR     SUB
 0269 DE 15                   LDX     SUM2
 026B BD 04 0F                JSR     SHFTR
 026E DE 53                   LDX     DATPTR
 0270 08                      INX
 0271 08                      INX
 0272 DF 53                   STX     DATPTR
 0274 DE 4F                   LDX     SAMP
 0276 08                      INX
 0277 DF 4F                   STX     SAMP
 0279 9C 59                   CPX     SAMPND
 027B 26 03                   BNE     FLT11
 027D 7C 00 67                INC     ENDFLG
 0280 7A 00 44       FLT11    DEC     RCNT
 0283 26 D1                   BNE     FLT1
 0285 C6 10                   LDA B   #$10
 0287 D7 44                   STA B   RCNT
 0289 7F 00 14                CLR     SUM1
 028C 7F 00 15                CLR     SUM2
 028F 7F 00 16                CLR     SUM3
 0292 CE 00 20                LDX     #REGS
 0295 DF 00          FLT2     STX     XTEMP
 0297 CE 00 0E                LDX     #A1
 029A A6 06          FLT3     LDA A   6,X
 029C A7 00                   STA A   0,X
 029E 08                      INX
 029F 8C 00 11                CPX     #B1
 02A2 26 F6                   BNE     FLT3
 02A4 7F 00 11                CLR     B1
 02A7 DE 00                   LDX     XTEMP
 02A9 EE 00                   LDX     0,X
 02AB 2A 03                   BPL     FLT4
 02AD 7A 00 11                DEC     B1
 02B0 DF 12          FLT4     STX     B2
 02B2 BD 03 E9                JSR     ADD
 02B5 DE 00                   LDX     XTEMP
 02B7 08                      INX
 02B8 08                      INX
```

```
02B9 8C 00 40             CPX    #REGSND
02BC 26 D7                BNE    FLT2
02BE 96 14                LDA A  SUM1
02C0 97 4C                STA A  TSUM1
02C2 97 06                STA A  MLTPR1
02C4 DE 15                LDX    SUM2
02C6 DF 4D                STX    TSUM2
02C8 DF 07                STX    MLTPR2
02CA CE 06 40             LDX    #$0640
02CD DF 04                STX    MLTCD1
02CF BD 03 47             JSR    MULT
02D2 DE 0A                LDX    PROD2
02D4 DF 48                STX    RDOT1
02D6 D6 4C                LDA B  TSUM1
02D8 D7 06                STA B  MLTPR1
02DA DE 4D                LDX    TSUM2
02DC DF 07                STX    MLTPR2
02DE CE 10 00             LDX    #$1000
02E1 DF 04                STX    MLTCD1
02E3 BD 03 47             JSR    MULT
02E6 96 09                LDA A  PROD1
02E8 97 11                STA A  B1
02EA DE 0A                LDX    PROD2
02EC DF 12                STX    B2
02EE DE 65                LDX    RDI
02F0 DF 0F                STX    A2
02F2 7F 00 0E             CLR    A1
02F5 BD 03 E9             JSR    ADD
02F8 DE 15                LDX    SUM2
02FA DF 65                STX    RDI
02FC D6 4C                LDA B  TSUM1
02FE D7 06                STA B  MLTPR1
0300 DE 4D                LDX    TSUM2
0302 DF 07                STX    MLTPR2
0304 CE 17 80             LDX    #$1780
0307 DF 04                STX    MLTCD1
0309 BD 03 47             JSR    MULT
030C 96 09                LDA A  PROD1
030E 97 11                STA A  B1
0310 DE 0A                LDX    PROD2
0312 DF 12                STX    B2
0314 BD 03 E9             JSR    ADD
0317 DE 15                LDX    SUM2
0319 DF 4A                STX    RE1
031B DE 55        OUT     LDX    REPTR
031D 96 4A                LDA A  RE1
031F D6 4B                LDA B  RE2
0321 A7 00                STA A  0,X
0323 E7 01                STA B  1,X
```

```
0325 08                 INX
0326 08                 INX
0327 DF 55              STX     REPTR
0329 DE 57      OUT1    LDX     RDOTPT
032B 96 48              LDA A   RDOT1
032D D6 49              LDA B   RDOT2
032F A7 00              STA A   0,X
0331 E7 01              STA B   1,X
0333 08                 INX
0334 08                 INX
0335 DF 57              STX     RDOTPT
0337 7D 00 67           TST     ENDFLG
033A 26 03              BNE     END
033C 7E 02 56           JMP     FLT1
033F DE 4F      END     LDX     SAMP
0341 09                 DEX
0342 DF 59              STX     SAMPND
0344 7E 04 C7           JMP     PRINTR
                *
                *   3 BYTE X 2 BYTE 2'S COMPLEMENT MULTIPLY
                *
0347 DF 00      MULT    STX     XTEMP
0349 CE 00 02           LDX     #SGN
034C 6F 00              CLR     0,X
034E 6C 00              INC     0,X
0350 A6 02              LDA A   2,X
0352 2A 0B              BPL     MULT1
0354 E6 03              LDA B   3,X
0356 BD 03 E1           JSR     NEGATE
0359 A7 02              STA A   2,X
035B E7 03              STA B   3,X
035D 6A 00              DEC     0,X
035F A6 04      MULT1   LDA A   4,X
0361 2A 14              BPL     MULT2
0363 A6 05              LDA A   5,X
0365 E6 06              LDA B   6,X
0367 BD 03 E1           JSR     NEGATE
036A A7 05              STA A   5,X
036C E7 06              STA B   6,X
036E A6 04              LDA A   4,X
0370 BD 03 E2           JSR     NEG4
0373 A7 04              STA A   4,X
0375 6A 00              DEC     0,X
0377 86 E7      MULT2   LDA A   #$E7
0379 A7 01              STA A   1,X
037B 4F                 CLR A
037C 5F                 CLR B
037D 6C 01      MULT3   INC     1,X
037F 27 16              BEQ     MULT4
```

```
0381 64 04              LSR     4,X
0383 66 05              ROR     5,X
0385 66 06              ROR     6,X
0387 24 04              BCC     MULT31
0389 EB 03              ADD B   3,X
038B A9 02              ADC A   2,X
038D 44         MULT31  LSR A
038E 56                 ROR B
038F 66 09              ROR     9,X
0391 66 0A              ROR     10,X
0393 66 0B              ROR     11,X
0395 20 E6              BRA     MULT3
0397 A7 07      MULT4   STA A   7,X
0399 E7 08              STA B   8,X
039B 7D 00 5D   ROUND1  TST     ROUND
039E 27 18              BEQ     MULT5
03A0 7D 00 0C           TST     PROD4
03A3 2A 0D              BPL     ROUND2
03A5 7C 00 0B           INC     PROD3
03A8 26 08              BNE     ROUND2
03AA 7C 00 0A           INC     PROD2
03AD 26 03              BNE     ROUND2
03AF 7C 00 09           INC     PROD1
03B2 7F 00 0C   ROUND2  CLR     PROD4
03B5 7F 00 0D           CLR     PROD5
03B8 66 00      MULT5   ROR     0,X
03BA 25 1D              BCS     MULTND
03BC A6 0A              LDA A   10,X
03BE E6 0B              LDA B   11,X
03C0 BD 03 E1           JSR     NEGATE
03C3 A7 0A              STA A   10,X
03C5 E7 0B              STA B   11,X
03C7 A6 08              LDA A   8,X
03C9 E6 09              LDA B   9,X
03CB BD 03 DC           JSR     NEG3
03CE A7 08              STA A   8,X
03D0 E7 09              STA B   9,X
03D2 A6 07              LDA A   7,X
03D4 BD 03 E2           JSR     NEG4
03D7 A7 07              STA A   7,X
03D9 DE 00      MULTND  LDX     XTEMP
03DB 39                 RTS
                *
                * 2'S COMPLEMENT ROUTINE
                *
03DC 24 03      NEG3    BCC     NEGATE
03DE 53                 COM B
03DF 20 06              BRA     NEG1
03E1 50         NEGATE  NEG B
```

```
03E2 25 03      NEG4     BCS     NEG1
03E4 40                  NEG A
03E5 20 01               BRA     NEG2
03E7 43         NEG1     COM A
03E8 39         NEG2     RTS
                ◆
                ◆ 3 BYTE ADDITION ROUTINE
                ◆
03E9 D6 10      ADD      LDA B   A3
03EB 96 0F               LDA A   A2
03ED DB 13               ADD B   B3
03EF 99 12               ADC A   B2
03F1 D7 16               STA B   SUM3
03F3 97 15               STA A   SUM2
03F5 96 0E               LDA A   A1
03F7 99 11               ADC A   B1
03F9 97 14               STA A   SUM1
03FB 39                  RTS
                ◆
                ◆ 3 BYTE SUBTRACTION ROUTINE
                ◆
03FC D6 10      SUB      LDA B   A3
03FE 96 0F               LDA A   A2
0400 D0 13               SUB B   B3
0402 92 12               SBC A   B2
0404 D7 16               STA B   SUM3
0406 97 15               STA A   SUM2
0408 96 0E               LDA A   A1
040A 92 11               SBC A   B1
040C 97 14               STA A   SUM1
040E 39                  RTS
                ◆
                ◆ ROUTINE TO SHIFT DATA IN REGS
                ◆
040F DF 1E      SHFTR    STX     RTEMP
0411 CE 00 41            LDX     #$0041
0414 E6 00      SHFTR1   LDA B   0,X
0416 E7 02               STA B   2,X
0418 09                  DEX
0419 8C 00 1D            CPX     #$001D
041C 26 F6               BNE     SHFTR1
041E 39                  RTS
                ◆
041F 0D         INIT1    FCB     $D,$A,$A,$A,$A,$A,$A
0420 0A 0A
0422 0A 0A
0424 0A 0A
0426 46                  FCC     /FILTER 5 MICROPROCESSOR/
0427 49 4C
```

```
 0429 54 45
 042B 52 20
 042D 35 20
 042F 4D 49
 0431 43 52
 0433 4F 50
 0435 52 4F
 0437 43 45
 0439 53 53
 043B 4F 52
 043D 20                 FCC    / SIMULATION RUN/
 043E 53 49
 0440 4D 55
 0442 4C 41
 0444 54 49
 0446 4F 4E
 0448 20 52
 044A 55 4E
 044C 0D                 FCB    $D,$A,$A
 044D 0A 0A
 044F 49                 FCC    /INPUT CHOICE?/
 0450 4E 50
 0452 55 54
 0454 20 43
 0456 48 4F
 0458 49 43
 045A 45 3F
 045C 0D                 FCB    $D,$A
 045D 0A
 045E 28                 FCC    /(SIGNAL=0,NOISE=1,/
 045F 53 49
 0461 47 4E
 0463 41 4C
 0465 3D 30
 0467 2C 4E
 0469 4F 49
 046B 53 45
 046D 3D 31
 046F 2C
 0470 53                 FCC    /SIGNAL+NOISE=2) /
 0471 49 47
 0473 4E 41
 0475 4C 2B
 0477 4E 4F
 0479 49 53
 047B 45 3D
 047D 32 29
 047F 20
 0480 04                 FCB    04
```

```
FILTER 5                         DECEMBER 19, 1978

 0481 0D        INIT2   FCB    $D,$A,$A
 0482 0A 0A
 0484 4E                FCC    /NUMBER OF /
 0485 55 4D
 0487 42 45
 0489 52 20
 048B 4F 46
 048D 20
 048E 53                FCC    /SAMPLES TO BE RUN?/
 048F 41 4D
 0491 50 4C
 0493 45 53
 0495 20 54
 0497 4F 20
 0499 42 45
 049B 20 52
 049D 55 4E
 049F 3F
 04A0 0D                FCB    $D,$A
 04A1 0A
 04A2 28                FCC    /(ENTER A 4 DIGIT /
 04A3 45 4E
 04A5 54 45
 04A7 52 20
 04A9 41 20
 04AB 34 20
 04AD 44 49
 04AF 47 49
 04B1 54 20
 04B3 48                FCC    /HEXIDECIMAL VALUE) /
 04B4 45 58
 04B6 49 44
 04B8 45 43
 04BA 49 4D
 04BC 41 4C
 04BE 20 56
 04C0 41 4C
 04C2 55 45
 04C4 29 20
 04C6 04                FCB    04
                *
                *
                *
                *  FILTER DATA PRINTER PROGRAM
                *
 04C7 CE 00 10  PRINTR  LDX    #$0010
 04CA DF 4F             STX    SAMP
 04CC CE 18 1E          LDX    #$181E
 04CF DF 51             STX    RAMPTR
```

```
04D1 CE 30 00            LDX    #$3000
04D4 DF 55               STX    REPTR
04D6 CE 38 00            LDX    #$3800
04D9 DF 57               STX    RDOTPT
04DB CE 06 11            LDX    #HEAD1
04DE BD E1 4B            JSR    $E14B      MINIBUG PDATA1
04E1 96 5C               LDA A  TYPE
04E3 44                  LSR A
04E4 24 0B               BCC    PRINT1
04E6 CE 06 3C            LDX    #NHEAD
04E9 BD E1 4B            JSR    $E14B      MINIBUG PDATA1
04EC CE 20 1E            LDX    #$201E
04EF 20 17               BRA    PRINT3
04F1 44         PRINT1   LSR A
04F2 24 0B               BCC    PRINT2
04F4 CE 06 47            LDX    #RNHEAD
04F7 BD E1 4B            JSR    $E14B      MINIBUG PDATA1
04FA CE 28 1E            LDX    #$281E
04FD 20 09               BRA    PRINT3
04FF CE 06 31   PRINT2   LDX    #RHEAD
0502 BD E1 4B            JSR    $E14B      MINBUG PDATA1
0505 CE 18 1E            LDX    #$181E
0508 DF 53      PRINT3   STX    DATPTR
050A CE 06 52            LDX    #HEAD2
050D BD E1 4B            JSR    $E14B      MINIBUG PDATA1
0510 C6 05               LDA B  #$05
0512 CE 06 6D            LDX    #HEAD4
0515 20 09               BRA    PRINT5
0517 CE 06 79   PRINT4   LDX    #HEAD5
051A BD E1 4B            JSR    $E14B      MINIBUG PDATA1
051D CE 06 6C            LDX    #HEAD3
0520 BD E1 4B   PRINT5   JSR    $E14B      MINBUG PDATA1
0523 5A                  DEC B
0524 26 F1               BNE    PRINT4
0526 CE 06 7B   LOOP     LDX    #HEAD6
0529 BD E1 4B            JSR    $E14B      MINIBUG PDATA1
052C CE 00 4F            LDX    #SAMP
052F DF 00               STX    XTEMP
0531 20 2D               BRA    LOOP5
0533 CE 06 85   LOOP1    LDX    #HEAD7
0536 BD E1 4B            JSR    $E14B      MINIBUG PDATA1
0539 DE 00               LDX    XTEMP
053B 8C 00 57            CPX    #RDOTPT
053E 26 1E               BNE    LOOP3
0540 86 20               LDA A  #$20
0542 BD E1 26            JSR    $E126      OUTCH
0545 EE 00               LDX    0,X
0547 E6 01               LDA B  1,X
0549 A6 00               LDA A  0,X
```

```
054B 2A 0B                 BPL    LOOP2
054D 36                    PSH A
054E CE 06 8E              LDX    #MINUS
0551 BD E1 4B              JSR    $E14B      MINIBUG PDATA1
0554 32                    PUL A
0555 BD 03 E1              JSR    NEGATE
0558 97 5F        LOOP2    STA A  C1
055A D7 60                 STA B  C2
055C 20 06                 BRA    LOOP4
055E EE 00        LOOP3    LDX    0,X
0560 EE 00        LOOP5    LDX    0,X
0562 DF 5F                 STX    C1
0564 BD 05 B6     LOOP4    JSR    CONV
0567 DE 00                 LDX    XTEMP
0569 08                    INX
056A 08                    INX
056B DF 00                 STX    XTEMP
056D 8C 00 59              CPX    #SAMPND
0570 26 C1                 BNE    LOOP1
0572 96 51                 LDA A  RAMPTR
0574 D6 52                 LDA B  RAMPTR+1
0576 CB 20                 ADD B  #$20
0578 89 00                 ADC A  #$00
057A 97 51                 STA A  RAMPTR
057C D7 52                 STA B  RAMPTR+1
057E 96 53                 LDA A  DATPTR
0580 D6 54                 LDA B  DATPTR+1
0582 CB 20                 ADD B  #$20
0584 89 00                 ADC A  #$00
0586 97 53                 STA A  DATPTR
0588 D7 54                 STA B  DATPTR+1
058A DE 55                 LDX    REPTR
058C 08                    INX
058D 08                    INX
058E DF 55                 STX    REPTR
0590 DE 57                 LDX    RDOTPT
0592 08                    INX
0593 08                    INX
0594 DF 57                 STX    RDOTPT
0596 DE 4F                 LDX    SAMP
0598 9C 59                 CPX    SAMPND
059A 27 0F                 BEQ    PEND
059C 96 4F                 LDA A  SAMP
059E D6 50                 LDA B  SAMP+1
05A0 CB 10                 ADD B  #$10
05A2 89 00                 ADC A  #$00
05A4 97 4F                 STA A  SAMP
05A6 D7 50                 STA B  SAMP+1
05A8 7E 05 26              JMP    LOOP
```

```
05AB 86 0A      PEND    LDA A  #$0A
05AD C6 05              LDA B  #$05
05AF BD E1 26   PEND1   JSR    $E126      MINIBUG OUTCH
05B2 5A                 DEC B
05B3 26 FA              BNE    PEND1
05B5 3F                 SWI
                *
                *
05B6 7F 00 5E   CONV    CLR    NFLAG
05B9 7D 00 5F           TST    C1
05BC 2A 03              BPL    CONV1
05BE 7A 00 5E           DEC    NFLAG
05C1 CE 27 10   CONV1   LDX    #$2710     10,000
05C4 BD 05 E1           JSR    FACTOR
05C7 CE 03 E8           LDX    #$03E8     1,000
05CA BD 05 E1           JSR    FACTOR
05CD CE 00 64           LDX    #$0064     100
05D0 BD 05 E1           JSR    FACTOR
05D3 CE 00 0A           LDX    #$000A     10
05D6 BD 05 E1           JSR    FACTOR
05D9 96 60              LDA A  C2
05DB 8A 30              ORA A  #$30
05DD BD E1 26           JSR    $E126      MINIBUG OUTCH
05E0 39                 RTS
                *
                *
05E1 DF 61      FACTOR  STX    D1
05E3 7F 00 5B           CLR    DIGIT
05E6 BD 06 04   FACT    JSR    SUB2BY
05E9 2B 0C              BMI    FACTND
05EB 7F 00 5E           CLR    NFLAG
05EE 7C 00 5B   FACT1   INC    DIGIT
05F1 DE 63              LDX    DIFF1
05F3 DF 5F              STX    C1
05F5 20 EF              BRA    FACT
05F7 7D 00 5E   FACTND  TST    NFLAG
05FA 2B F2              BMI    FACT1
05FC 96 5B              LDA A  DIGIT
05FE 8A 30              ORA A  #$30
0600 BD E1 26           JSR    $E126
0603 39                 RTS
                *
                *  2 BYTE SUBTRACTION ROUTINE
                *
0604 D6 60      SUB2BY  LDA B  C2
0606 96 5F              LDA A  C1
0608 D0 62              SUB B  D2
060A 92 61              SBC A  D1
060C D7 64              STA B  DIFF2
```

```
 060E 97 63              STA A  DIFF1
 0610 39                 RTS
                  ◆
                  ◆
 0611 0D         HEAD1   FCB    $0D,$0A,$0A,$0A,$0A
 0612 0A 0A
 0614 0A 0A
 0616 20                 FCC    / SAMPLE    !     RAMP    ! /
 0617 53 41
 0619 4D 50
 061B 4C 45
 061D 20 20
 061F 20 20
 0621 21 20
 0623 20 20
 0625 20 52
 0627 41 4D
 0629 50 20
 062B 20 20
 062D 20 21
 062F 20
 0630 04                 FCB    $04
 0631 20         RHEAD   FCC    /   RAMP   /
 0632 20 20
 0634 52 41
 0636 4D 50
 0638 20 20
 063A 20
 063B 04                 FCB    $04
 063C 20         NHEAD   FCC    /   NOISE  /
 063D 20 20
 063F 4E 4F
 0641 49 53
 0643 45 20
 0645 20
 0646 04                 FCB    $04
 0647 52         RNHEAD  FCC    /RAMP+NOISE/
 0648 41 4D
 064A 50 2B
 064C 4E 4F
 064E 49 53
 0650 45
 0651 04                 FCB    $04
 0652 20         HEAD2   FCC    / !     RE    !     RDOT/
 0653 21 20
 0655 20 20
 0657 20 20
 0659 52 45
 065B 20 20
```

```
 065D 20 20
 065F 20 21
 0661 20 20
 0663 20 20
 0665 52 44
 0667 4F 54
 0669 0D            HEAD8    FCB     $0D,$0A,$04
 066A 0A 04
 066C 2D            HEAD3    FCC     /-/
 066D 2D            HEAD4    FCC     /------------/
 066E 2D 2D
 0670 2D 2D
 0672 2D 2D
 0674 2D 2D
 0676 2D 2D
 0678 04                     FCB     $04
 0679 21            HEAD5    FCB     $21,$04
 067A 04
 067B 00 0D         HEAD6    FDB     $0D,$0A,$20,$20,$04
 067D 00 0A
 067F 00 20
 0681 00 20
 0683 00 04
 0685 20            HEAD7    FCC     /     !    /
 0686 20 20
 0688 20 21
 068A 20 20
 068C 20
 068D 04                     FCB     $04
 068E 08            MINUS    FCB     $08,$2D,$04
 068F 2D 04
                             END
         NO ERROR(S) DETECTED


   SYMBOL TABLE:
A1        000E        A2        000F        A3        0010
ADD       03E9        B1        0011        B2        0012
B3        0013        C1        005F        C2        0060
CNT       0003        CONV      05B6        CONV1     05C1
D1        0061        D2        0062        DATPTR    0053
DIFF1     0063        DIFF2     0064        DIGIT     005B
END       033F        ENDFLG    0067        FACT      05E6
FACT1     05EE        FACTND    05F7        FACTOR    05E1
FLT       0200        FLT1      0256        FLT11     0280
FLT2      0295        FLT3      029A        FLT4      02B0
FLTA      0241        HEAD1     0611        HEAD2     0652
HEAD3     066C        HEAD4     066D        HEAD5     0679
```

```
FILTER 5                                    DECEMBER 19, 1978

HEAD6     067B          HEAD7     0685          HEAD8     0669
INIT1     041F          INIT2     0481          INPUT1    0226
INPUT2    022E          INPUT3    0231          LOOP      0526
LOOP1     0533          LOOP2     0558          LOOP3     055E
LOOP4     0564          LOOP5     0560          MINUS     068E
MLTCD1    0004          MLTCD2    0005          MLTPR1    0006
MLTPR2    0007          MLTPR3    0008          MULT      0347
MULT1     035F          MULT2     0377          MULT3     037D
MULT31    038D          MULT4     0397          MULT5     03B8
MULTND    03D9          NEG1      03E7          NEG2      03E8
NEG3      03DC          NEG4      03E2          NEGATE    03E1
NFLAG     005E          NHEAD     063C          OUT       031B
OUT1      0329          PEND      05CB          PEND1     05AF
PRINT1    04F1          PRINT2    04FF          PRINT3    0508
PRINT4    0517          PRINT5    0520          PRINTR    04C7
PROD1     0009          PROD2     000A          PROD3     000B
PROD4     000C          PROD5     000D          RAMPTR    0051
RCNT      0044          RCRCT1    0046          RCRCT2    0047
RDI       0065          RDOT1     0048          RDOT2     0049
RDOTPT    0057          RE1       004A          RE2       004B
REGS      0020          REGSND    0040          REPTR     0055
RHEAD     0631          RNHEAD    0647          ROUND     005D
ROUND1    039B          ROUND2    03B2          RTEMP     001E
SAMP      004F          SAMPND    0059          SGN       0002
SHFTR     040F          SHFTR1    0414          SKPFLG    0045
SUB       03FC          SUB2BY    0604          SUM1      0014
SUM2      0015          SUM3      0016          TSUM1     004C
TSUM2     004D          TSUM3     004E          TYPE      005C
XTEMP     0000
```

APPENDIX D

The program to determine variance reduction ratio from the z transfer function is presented on the following page.

PROGRAM TO DETERMINE VARIANCE REDUCTION RATIO FROM Z TRANSFER FUNCTION

```
10    DIMN(50),D(50)
15    S=0
20    PRINT"NUMBER OF TERMS RESULT IS TO BE CARRIED OUT = ";
25    INPUT T
40    PRINT"ORDER OF NUMERATOR = ";
50    INPUT A
60    FOR J=1 TO A+1
70    PRINT"N(";J-1;")=";
80    INPUT N(J)
90    NEXT J
100   PRINT"ORDER OF DENOMINATOR = ";
110   INPUT B
120   FOR J=1 TO B+1
130   PRINT"D(";J-1;")=";
140   INPUT D(J)
150   NEXT J
155   PRINT
160   IF A>=B THEN 210
170   A=B
180   FOR J=A+2 TO B+1
190   N(J)=0
200   NEXT J
210   FOR L=0 TO T
220   M=N(1)/D(1)
230   FOR J=2 TO B+1
240   N(J)=N(J)-M*D(J)
250   NEXT J
260   S=S+M**2
270   PRINT"H(";L;")=";M;TAB(28);"SUMMATION OF H**2 =";S
280   FOR J=1 TO A
290   N(J)=N(J+1)
300   NEXT J
310   N(A+1)=0
330   NEXT L
360   END

READY
```

APPENDIX E

A method for deriving a discrete system from a continuous system is to replace the integrators in the continuous system with numerical integrators.[9] The resulting discrete system will be different for each method of numerical integration used. The simplest method is Euler's approximation where the time derivative is approximated by

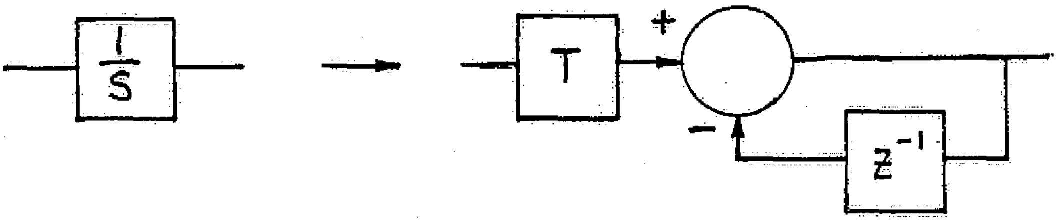
$$\frac{d}{dt}f(nT) \simeq \frac{f(nT) - f((n-1)T)}{T} \,. \tag{37}$$

Taking the Laplace operator of the left side of (37) and equating it to the z operator of the right side of (37) yields the mapping from the s-plane to the z-plane

$$s = \frac{1-z^{-1}}{T} \,. \tag{38}$$

The continuous integrator can then be replaced by

$$\frac{1}{s} = \frac{T}{1-z^{-1}} \,. \tag{39}$$



Although with this method a discrete system can be obtained for any continuous system, the discrete system may not be physically realizable on a digital computer. Due to the finite time required for computations, every feedback loop must contain a delay element.