THE EFFECTS OF SIGNAL QUANTIZATION ON COMPENSATORY TRACKING PERFORMANCE

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THESIS

The Effects of Signal Quantization On Compensatory Tracking Performance

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December 1972

Approved for public release; distribution unlimited.

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M.S., Naval Postgraduate School, 1972

Submitted in partial fulfillment of the
requirements for the degree of

AERONAUTICAL ENGINEER

from the

NAVAL POSTGRADUATE SCHOOL
December 1972

ABSTRACT

The effects of quantizing the displayed error were investigated in both single- and dual-axis critical compensatory tracking tasks and in cross-adaptive tracking tasks. Both first order and second order controlled elements were used, as well as an intermediate "1.5" order element. Quantization intervals investigated ran from 0 to 1.69 cm on a 10 cm by 10 cm display.

A digital computer program was written for use with a hybrid computer in order to mechanize the various types of tracking tasks used in this research and for future use at this facility.

Results of the critical tracking task runs indicate that the operator's performance deteriorates almost linearly as the quantization interval is increased. Cross-adaptive tracking task results indicate a pronounced increase in operator workload when quantization is used.

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LIST OF SYMBOLS

c	control force (N)
e	error (cm)
e_p	RMS error established by the operator during a cross-adaptive training run (cm)
e_{rms}	RMS error (cm)
E_c	error criterion (dimensionless)
K_A	secondary instability level control constant (rad/sec)
K_c	control sensitivity (cm/N or cm/sec/N)
K_D	display viewing gain (degrees visual arc/cm display deflection)
i	input (cm)
i_{rms}	RMS input (cm)
m	output (cm)
q	quantized error (cm)
s	Laplace operator
t	time (sec)
T	time constant (sec)
Y_c	controlled element transfer function
Y_p	operator (subject) transfer function
λ	instability level (rad/sec)
λ_o	initial instability level (rad/sec)
λ_c	critical instability level (rad/sec)
λ_D	dual-axis critical instability level (rad/sec)

λ_x	cross-adaptive instability level (rad/sec)
$\dot{\lambda}$	rate of increase of the instability level (rad/sec/sec)
$\dot{\lambda}_p$	maximum rate of increase of the instability level (rad/sec/sec)
$\dot{\lambda}_n$	maximum rate of decrease of the instability level (rad/sec/sec)
τ_e	operator's effective time delay (sec)
$\overline{(\ )}$	average or mean value
SD	standard deviation
$\|\ \|$	absolute value

ACKNOWLEDGEMENT

The author wishes to express his gratitude to his thesis advisor, Asst. Professor R. A. Hess, for his unbounded patience and support, as well as the donation of his time as the principle subject in this research. Without his assistance this thesis would not have been possible. A heartfelt "thanks" also goes to the author's family for their cheerful support during the long period of this research.

I. INTRODUCTION

A. MOTIVATION

In recent years, considerable success has been achieved in the field of human response investigations, both in operator modeling and in display optimization. Quasi-linear describing function models have been developed for use in predicting human performance in manual control systems. Specifically, the modeling of the human operator in compensatory tracking tasks is a well-documented art (e.g., see Ref. 1 or Ref. 2). Such modeling has been used both to predict and to explain experimental results.

One of the yet unexplored areas, however, is the effect of display signal quantization, such as would be encountered through the use of electroluminescent or gaseous-discharge displays. Some research has been documented in which a display utilizing a particular quantization interval is compared with other types of displays (e.g., see Ref. 2). The question of whether the chosen quantization intervals are representative of results which might be obtained from any other quantization interval is unanswered, however. It is to this problem that this research addresses itself.

Some questions which may arise concerning these types of quantized displays are:

1. Under what conditions will the display be utilized? This

question implicates a number of variables, among which are the effective lead equalization required of the operator for the task involved, any deterioration in performance of other associated or separate tasks, and the required precision of the task performance.

2. What quantization interval should be used? A practical limit on the quantization interval is obviously the error that can be safely tolerated in the task under consideration, but performance at quantization intervals up to and including that limit is an unknown at present.

3. Is there an optimum quantization interval? These questions form the basis of this research and can only be partially answered at present, utilizing all known pilot models and analysis techniques.

B. OBJECTIVES

The prime objective of this research is to provide the answers to the above questions, using compensatory[1] tracking tasks to compare human tracking performance at various quantization intervals with that achieved using a continuous presentation. A secondary objective is the generation of a laboratory procedure for future research involving compensatory tracking task performance at this facility.

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[1] Since all tracking tasks investigated in this research were compensatory tracking tasks, the work "compensatory" will be omitted in following discussions.

C. RESULTS OF PRELIMINARY INVESTIGATIONS

The required tracking tasks were mechanized on the hybrid computer system of the Electrical Engineering Laboratory at the U.S. Naval Postgraduate School. This hybrid computer consisted of the Scientific Data Systems 9300 digital computer and the COMCOR 5000 analog computer.

Early testing indicated that meaningful results could be obtained by concentrating on two different, yet related, operator parameters: operator effective time delay and a form of workload measurement. A "critical instability" task was chosen as one type of tracking task to be investigated. A critical task in one axis is shown in Figure 1. In this type of task, the controlled element in an operator-controlled closed-loop system is initially held nominally divergent. The divergence (instability) is then increased to the point of loss of control by the operator. It has been shown that this type of task is dominated by the operator's effective time delay, τ_e (Ref. 3). Both single- and dual-axis critical instability tasks were chosen for this research. A dual-axis tracking task is shown in Figure 2. It consists of two independent critical tasks, one in each axis, in which the instability level of each is increased at a common rate.

To investigate operator workload, the cross-coupled task of Reference 4 was chosen. A block diagram of this type of tracking task is shown in Figure 3. The underlying principle of this task is to "load" the operator with a secondary task in an attempt to measure

the primary task workload. The secondary task used is a first order subcritical tracking task[2] of variable divergence. The level of instability of the secondary task at the onset of deterioration of primary task performance is then taken as a measure of workload. It is also called a measure of "excess" or "reserve" capacity in that it yields a measure of how much reserve capacity the operator has to spare for the secondary task. In this type of task, the secondary task is "adaptive" in that it's instability level is controlled by the operator's performance of the primary task and, for this reason, the name "cross-adaptive" is sometimes applied. The term "cross-adaptive" will be used throughout this report.

Another concern in early testing was the interval of quantization. It was found that intervals of up to 1.69 cm were feasible. The intervals were chosen by dividing the positive half of the 4 inch by 4 inch display into 80, 20, 10, 7, 5, 4, and 3 intervals, corresponding to quantization intervals of 0.0635 cm, 0.2540 cm, 0.5080 cm, 0.7257 cm, 1.0160 cm, 1.2700 cm, and 1.6933 cm, respectively.

Preliminary investigations into the requirements necessary for accomplishment of the secondary objective, that of generating a useful laboratory procedure for tracking task performance measurements, indicated that it would be possible to design a master computer program

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[2] A subcritical task is one in which the divergent controlled element is held at a constant instability level below the critical instability level (the point at which loss of control is experienced).

which would incorporate both types of tracking tasks chosen for the research. It was also obvious that other tasks could readily be incorporated into the program. For this reason, both single- and dual-axis subcritical tracking tasks (see Figures 4 and 5) were built into the program, though they were not investigated in this research.

For the formal part of the investigation, three different controlled elements were chosen. Those used for the critical tasks are evident in Figures 1 and 2, while those chosen for the cross-adaptive tasks are shown in Figure 3. The first and second order controlled elements were selected primarily for the wide differences in lead equalization[3] required, but also in the interest of standardization with other research (e.g., see Ref. 2 or 4). The intermediate "1.5" order controlled element was selected to break the wide difference in lead equalization required for the first and second order controlled elements.

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[3] Lead equalization is the process of determining signal rate or acceleration. Lead generation is the application of lead equalization in the tracking process.

II. THEORY

A. CRITICAL INSTABILITY TRACKING TASKS

As previously mentioned, a "critical task" is one in which a human operator is required to manually control an increasingly divergent controlled element in closed-loop operation. In the first order case, the controlled element transfer function is

$$Y_c = \frac{\lambda}{s - \lambda}$$

where λ is the instability level. As λ is increased, increasing divergence (instability) of the control system results. The point at which the operator can no longer control the system is called the "critical instability level", λ_c, and has been shown to be approximately the inverse of the operator's effective time delay, τ_e. This time delay is an effective approximation of the net operator phase lag consisting of the various delays and lags involved in the eye/brain/limb/control-stick system. As $\lambda \rightarrow \lambda_c$, the operator's describing function can be shown to assume the form:

$$Y_p = K_p e^{-j\omega\tau_e}$$

This describing function may be approximated (Ref. 3) by:

$$Y_p = \frac{-(j\omega - 2/\tau_e)}{(j\omega + 2/\tau_e)}$$

The controlled element transfer function may be rewritten as:

$$Y_c = \frac{1/\tau}{j\omega - 1/\tau}$$

The product of Y_p and Y_c is then:

$$Y_p Y_c = \frac{-(j\omega - 2/\tau_e)(1/\tau)}{(j\omega + 2/\tau_e)(j\omega - 1/\tau)}$$

A Bode plot of this system transfer function indicates that, as λ is increased (τ decreased), the system finally goes unstable in an oscillatory mode. As this instability is increased, the system gain (frequency response) falls off rapidly until insufficicient gain remains to effectively counter the large amplitude oscillations of the system. This is the point of loss of control, and occurs approximately at the point where $\lambda = \lambda_c$ or $\tau = \tau_e$. The fact that the operator's behavior is tightly constrained (i.e., he is forced to avoid any lead or lag equalization) is documented in Reference 3.

The result of replacing the first order controlled element with a second order controlled element is to introduce another pole into the Bode plot, effectively speed up the onset of system gain roll-off, and require full lead equalization by the operator. The overall result is an increase in the operator's effective time delay, τ_e , and a decrease in the critical instability level, λ_c. The same effects are obtained from the "1.5" order controlled element, but to a lesser extent.

When utilized in two axes simultaneously, the term "dual-axis critical instability task" is applied. All the above comments apply equally well in this case, except that the critical value of instability is called the "dual-axis critical instability level", or simply the "dual-axis instability level", λ_D.

The critical instability level is primarily an operator-centered score, indicating that precise duplication of equipment and parameters is not necessary to achieve meaningful results. For this reason, the critical task is finding widespread popularity in the fields of control-stick sensitivity research, optimal display research, and secondary workload effects research, among others.

B. CROSS-ADAPTIVE TRACKING TASKS

The cross-adaptive tracking task of Reference 4 consists of any arbitrary primary task together with a subcritical secondary task. A subcritical task is mechanized in exactly the same manner as the critical task, except that the instability level is maintained at a subcritical level, i.e., below the critical instability level. In the cross-adaptive task, this subcritical instability level is coupled to the primary task in that its value depends upon primary task performance. In Reference 4, the primary task utilized was a subcritical task itself. An input was used for the primary task; none was used for the secondary task.

The basic principle of this type of tracking task is that the final score, the asymptotic value of the secondary instability level, is related to the amount of excess control capacity of the operator without the secondary task, i.e., in the unloaded condition. In other words, it measures the amount of workload required of the operator by the primary task.

Figure 3 shows a cross-adaptive task. The key to this type of task is the "unloaded" RMS error, e_p, which is that primary task RMS error established over a period of time during which the secondary instability level remains constant at a small nominal value. The value used in this research was 1.0 rad/sec. During the cross-adaptive tracking, the secondary instability level is controlled in the following manner: the instantaneous primary task error is compared with some multiple of the unloaded RMS error. If the primary task error is the smaller of the two, indicating that the operator's instantaneous performance of the primary task is better than his unloaded performance, the secondary instability level is allowed to increase, thus increasing the operator's workload. If, on the other hand, the instantaneous primary task error is larger, indicating poorer performance of the primary task than that obtained in the unloaded case, the secondary instability is decreased in order to ease the workload placed on the operator. Eventually a stable value of the instability level should be reached. This value is then taken as the "score" for the run and is given the name "cross-adaptive instability level", λ_x.

A more accurate score, as suggested in Reference 4, would be some function of both λ_x and e_p. No function has yet been devised, however, so only the raw λ_x score was used in this research.

The mechanization of this type of task is indicated in Figure 3. The instantaneous, absolute primary error is divided by the unloaded RMS error, giving a dimensionless quantity which is subtracted from

E_c, the error criterion. This result is then multiplied by a constant integrating factor, K_A, to yield the rate of increase (decrease) of the secondary instability level. This integrating rate is clipped at a maximum rate of increase, $\dot{\lambda}_p$, and a maximum rate of decrease, $\dot{\lambda}_n$, to prevent excessive gyrations of the secondary instability level. The values used for K_A, $\dot{\lambda}_p$, and $\dot{\lambda}_n$ were those used with success in Reference 5, while the value of E_c was that suggested in Reference 4. All values are shown in Figure 3.

The theoretical by-products of this type of secondary task loading consist of an increase in the operator's effective delay time, τ_e, a decrease in the lead equalization, and an increase in the primary task RMS error. Reference 4 reports experimental validation of this theory.

By maintaining the same secondary task, a variety of primary tasks may be compared with regard to operator workload. Another possibility is the ability to compare a number of primary task displays. Both were accomplished in this research, using the cross-adaptive task to measure workload for the non-quantized and quantized cases for the three different controlled elements mentioned previously. It should be noted that the secondary task controlled element was not varied, nor was any quantization introduced into the secondary task in the interests of standardization between runs. It should also be noted that the three controlled elements used for the cross-adaptive task are not identical to those used in critical tracking, but the basic theory is the same in that more lead generation is required for the higher orders than for the first order case.

III. THE EXPERIMENT

A. BACKGROUND

Essential to the mechanization of the tracking tasks investigated in this research was the analog computer, along with its external equipment. This external equipment consisted of two audio frequency signal generators, two low-pass filters, a dual-axis cathode-ray tube display, a dual-axis rigid control stick, and an eight-pen strip-chart recorder. Utilizing this equipment, any of the tasks previously mentioned could be mechanized and runs could be made with one exception: signal quantization would not be possible. To accomplish signal quantization, a digital computer was used. From this supporting role in the early stages of the research, the digital computer program has been enlarged and refined to the point where it completely controls the analog computer.

Initial plans were to modify the analog computer patchboard wiring for each different type of tracking task investigated, with the digital computer providing nothing more than signal quantization and mode control (RESET, COMPUTE, HOLD) of the analog computer. The advantages and possibilities of the digital computer were readily apparent, however. Thus, on-line data computation for subcritical and cross-adaptive tasks was added to the digital computer program, thus providing RMS input, mean input, RMS error, and mean error. Early experiments also indicated that it would be possible to have a completely general analog computer patchboard configuration, with

selected circuits being used for the various types of tracking tasks. This was accomplished by judicious use of potentiometers which were set either to zero or one (actually 0.9999) by the digital computer depending upon whether the particular circuit containing that potentiometer was to be included in the analog schematic for the type of run selected or whether the circuit was to be ommitted from the schematic.

As they are configured at the time of this writing, the analog computer patchboard configuration and the digital computer program are coded to present any of the tracking tasks listed in Table 1 at any quantization interval.

B. THE ANALOG COMPUTER

The analog computer is coupled to the digital computer via "trunk lines", thus forming the hybrid computer. Also associated with the analog computer are the pieces of equipment mentioned previously. The function of the control stick is obvious, as is that of the display. One signal generator provides the control stick with its "power", while the other provides a steady horizontal line on the display when tracking in the vertical axis only. A low-pass filter is used for the input to the vertical axis of the display and another is used for the horizontal axis input when tracking in two directions is implemented. These filters are used to remove high frequency noise originating in the analog computer. The strip-chart recorder provides time histories of the tracking runs.

The "completely general" analog patchboard configuration mentioned previously is shown in the form of an analog schematic in

Figure 6. All of the potentiometers shown are controlled by the digital computer with the exception of the 400-series potentiometers. These are handset potentiometers and are used for control stick/ display calibration. By setting selected digital-controlled potentiometers to zero or one, the analog computer can be programmed to handle a large variety of tracking tasks. The resulting analog computer schematics are shown in Figures 7-21. Figure 22 explains the symbols used in these figures.

The analog computer also provides a low-frequency random noise generator of predictable RMS amplitude and bandwidth for use as the input in subcritical or cross-adaptive tasks, although the output of this noise generator must be further filtered to provide the small bandwidth required for these tracking tasks.

C. THE DIGITAL COMPUTER

The digital computer used includes a built-in clock counter which operates at a frequency of 60 Hz and which is used for the functions of quantization and on-line data computation. Quantization is provided at the rate of 10 samples per second using a modified floating point-to-integer conversion. On-line data computation occurs at the same rate and provides, for subcritical and cross-adaptive tasks, the RMS input, mean input, RMS error, and mean error. For cross-adaptive tasks, the digital computer governs the rate of movement of the secondary instability level by comparing the primary task instantaneous error

with a pre-established RMS error.[4] For critical tasks, the only output from the digital computer is the critical instability level.

Other functions of the digital computer include:

1. Stopping the run when either the time limit or the display limit is exceeded.

2. Printing the data mentioned above.

3. Proceeding automatically to the next run after a delay of about fifteen seconds (if so desired by the operator, who uses a coding system to select the number of runs desired at a given quantization level for a certain tracking task type).

4. Stopping the program when the desired number of runs is completed.

5. Selecting the five best runs (if the number of runs completed is five or more) and computing the mean and standard deviation of all applicable parameters for those five runs.

Also available in the coding system is the option to change tracking type or quantization level or number of runs desired without re-compiling the entire program deck.

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[4] All runs were made using an RMS error that had been established as an average of at least five training runs during which the secondary instability level was held constant at 1.0 rad/sec. At the time of this writing, however, the digital program had been modified to include a routine which sampled the primary RMS error during the initial part of the run. When this RMS error stabilized, the computer stored it as its pre-established RMS error and proceeded with the actual cross-adaptive run, in which the secondary instability level was varied depending upon the operator's performance of the primary task.

The computer program, along with detailed instructions for its implementation, is contained in the Computer Program section of this report.

D. PROCEDURE

Two subjects were used in this research: the author and his thesis advisor. The author (Subject WT) had no previous tracking experience but was a military jet aviator. His thesis advisor (Subject RH) had some tracking experience but no aviation experience. The runs for the various tracking tasks were conducted by both subjects over a period of about two months. All runs were conducted in a brightly-lit room (the Electrical Engineering Computer Laboratory at the U.S. Naval Postgraduate School). An attempt was made to conduct the runs at times when no distractions were present. This was accomplished in about 70% of the cases, with about that same percentage of the runs being conducted during the hours 2000-0100.

As previously mentioned, the quantization intervals investigated were: 0.0635 cm, 0.2540 cm, 0.5080 cm, 0.7257 cm, 1.0160 cm, 1.2700 cm, and 1.6933 cm. Runs were made at each of these quantization intervals plus the continuous case for each tracking task considered.

The equipment is shown in Figure 23. The display area was limited to a 4-inch square. In single-axis tracking, a bright green horizontal line 0.10 cm wide was displayed, while in dual-axis tracking a 0.15 cm diameter dot was presented to the operator. The subject sat in a

chair upon which the control stick was mounted. Equipment placement was adjusted to maintain a constant 52 cm eye-to-display distance. The control stick was a rigid force stick about 4 inches long with a three-fourth inch ball on the end. The control sensitivities varied for the different controlled elements. (See Figures 1-5)

1. Critical Tasks

For both single-axis and dual-axis critical tracking, the three controlled elements remained the same. The order in which these three controlled elements were presented to the subject was always first order, "1.5" order, and second order, i.e., all of the required runs at all quantization intervals were completed with the first order controlled element before proceeding to the "1.5" order controlled element, etc.

The display viewing gain of 1.0 degrees of visula arc per centimeter of display deflection was chosen in the interests of standardization with prior research (see Ref. 4), as was the first order controlled element control sensitivity of 1.0 cm/N. The control sensitivity was increased to 3.33 cm/sec/N for the "1.5" order and the second order controlled elements.

The initial value of the instability level was nominally set at a very comfortable and easily-controlled 1.0 rad/sec. The instability level was increased at a constant rate of 0.1 rad/sec/sec until the critical instability level was reached. (References 3 and 6 use two different rates or increase of the instability level, the slower of the two being

used after a certain error criterion has been exceeded, but early correlation of results of this research with that of those references proved that this was not necessary.)

No input was used; the only system excitation was that caused by the operator.

No formal training runs were used; instead, each subject was administered twenty runs at each quantization interval, with the five best being used for data purposes. The resulting critical instability levels may be slightly higher than those reported elsewhere, but consistency among the quantization intervals assured that the purpose of this research was served: that of determining the effects of quantization upon compensatory tracking performance.

Runs were administered in groups of twenty, with about fifteen seconds between each run. Typical run lengths varied from about 60 seconds (first order single-axis) to uncontrollable for any length of time (second order dual-axis). When practicable, all quantization levels for a given controlled element were completed at one sitting, i.e., twenty runs at one quantization interval, another rest period, etc., for a total of 160 runs for each controlled element for both single- and dual-axis tracking. Thus, each subject experienced 960 runs during the critical task portion of the formal research. Sample time histories of the dual-axis critical tracking task at all the various quantization intervals are shown in Figures 24-30.

2. Cross-Adaptive Tasks

As for the critical task portion of the formal runs, all three controlled elements were investigated, with the order of presentation remaining the same, i.e., first order, "1.5" order, and second order. Not all quantization intervals were investigated, however. For each controlled element, only one quantization interval was used, along with the continuous case.

A primary task input was used in the form of the output from a low-frequency noise generator which was built into the analog computer. This input was further filtered to maintain an input bandwidth of 2.0 rad/sec for all three controlled elements. The input RMS amplitude was initially also held constant at 0.50 cm, but early investigations indicated that, for the first order controlled element, RMS errors were so low that meaningful results of cross-adaptive tracking could not be obtained. For this reason, the input RMS amplitudes used for the formal runs were 1.00 cm, 0.50 cm, and 0.50 cm for the first order, "1.5" order, and second order controlled elements, respectively.

A variation of the cross-coupled task reported in Reference 4 was utilized. In that research, the cross-adaptive tracking task runs lasted approximately 150-180 seconds. The first 20-30 seconds consisted of training in that the secondary instability level was held constant at 0.2 rad/sec while the primary task RMS error was allowed to stabilize. Once stabilization was achieved, the actual cross-adaptive

task was commenced. For the purposes of this research, it was felt that those run lengths were prohibitive, i.e., attempting to track a quantized display for those lengths of time would induce operator fatigue and render the results useless. A compromise was achieved by separating the training segment from the tracking segment and by utilizing formal training, or "RMS error establishing" runs. The run length of both the training and cross-adaptive tracking runs was then limited to 120 seconds. A typical time history of a cross-adaptive tracking run for the continuous case is shown in Figure 31.

During initial investigations, an error criterion of 1.2 was used, as suggested in Reference 4. Results with this error criterion, however, indicated that extremely high cross-adaptive instability levels were achieved and, in a number of cases, the dual-axis critical instability level was reached in the secondary task, i.e., the operator lost control of the secondary task before primary task degradation was observed. This indicated that the criterion for measuring primary task degradation would have to be modified, as it was, by changing the error criterion to 1.0. Promising results were obtained in this fashion leading to the use of an error criterion of 1.0 for the formal tracking runs.

During the formal portion of the runs, ten training runs were conducted to determine RMS error. The average of the best five runs (lowest RMS error) was then used as the criterion for the following 8-10 cross-adaptive tracking runs. The above sequence was completed

for the continuous case first, followed by the quantized case, for each controlled element. The order of presentation of the controlled elements remained the same as for the formal critical instability runs.

Subject RH was tested first, followed by Subject WT. Meaningful data was obtained from the runs of Subject RH, but difficulties were encountered during the runs of Subject WT. Due to limits on the availability of the equipment, the training runs for Subject WT were separated in time from his cross-adaptive tracking runs. A learning curve effect then set in with the result that his RMS errors for the cross-adaptive runs were, in some cases, lower than those obtained during the training run portion of the research. This, in turn, resulted in either loss of control of the secondary task or extremely high (and constant for all cases considered) cross-adaptive instability levels with no degradation of primary task performance as perceived by the digital computer, which was using as a criterion the RMS error established during the training runs. Since meaningful results could not be obtained, formal cross-adaptive tracking runs were not used for Subject WT. This also led to re-incorporation of the training and tracking portions into the same run.[5]

E. DATA ANALYSIS

Almost all data analysis in this research was done by the digital computer, either on-line or off-line. The one exception was the

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[5] See CONCLUSIONS AND RECOMMENDATIONS

cross-adaptive instability levels, which were visually sighted from strip-chart recordings of the filtered instability levels. The performance measures used are contained in Appendix C. For the critical tasks, only the critical instability level was used as a measure of performance. For the cross-adaptive tasks, the mean input, RMS input, mean error, and RMS error were computed by the digital computer. For both cases, the best five runs were selected and the average and standard deviation of those five computed. This was accomplished automatically by the digital computer for both the critical task runs and the cross-adaptive training runs. Due to the visual sighting of the strip-chart recordings to determine the cross-adaptive instability levels, the best five and the average and standard deviation for those five runs were not computed by the digital computer.

IV. RESULTS

The results obtained for the critical task runs are listed in Tables 2 and 3 and are shown graphically in Figures 32-35. For the single-axis case, an almost linear relationship between quantization interval and critical instability level is apparent. This seems to indicate that the operator's effective time delay is directly proportional to the quantization interval.

An interesting observation is to be made concerning the 0.7257 cm quantization interval: in the first order single-axis case, for both subjects, the critical instability level seems to fall above the "almost linear" pattern. Several possible explanations are evident. One of these concerns the learning curve effect in that the operator, after 80 runs, 60 of which were quantized, could have finally adapted to the quantization scheme, whether he changed his tracking philosophy or not. Another possible explanation is that his tracking philosophy could have changed due to the increasing size of the quantized "jumps" in the display. A third explanation could be that there exists an optimal quantization interval in this region. More research would be needed to pinpoint the reason for this phenomenon.

It is also interesting to note that this phenomenon occurred only for the first order controlled element; when any lead was required of the operator, the instability levels for the various quantization intervals more nearly followed the linear pattern suggested above.

For the dual-axis cases, the above comments apply equally well, with one additional comment. No data were available for the higher order, higher quantized cases becuase they were controllable for less than about 10 seconds.

The cross-adaptive tracking task results are contained in Table 4 and the cross-adaptive instability levels are shown in Figure 36. A definite effect of quantization is again evident. Although the first order case connot be compared with the other two cases due to the differences in both quantization interval and RMS input amplitude, the quantized and non-quantized cases may be compared for each controlled element. The result of such a comparison is an obvious indication that the operator workload significantly increases when quantization is used.

In the training runs of Table 4, the percentage increase in RMS tracking error in going from continuous to quantized displays was 3. 6, 5. 3, and 3. 5% for the first order, "1. 5" order, and second order tasks, respectively, These relatively small decrements in tracking performance, however, were achieved at the cost of significantly large workload levels in the quantized cases (see Figure 36).

Two problem areas in the mechanization of the cross-adaptive task were evident. The first concerned the primary task input. A random noise generator was used with a deterministic RMS amplitude and bandwidth. The input was further filtered, so no problem was experienced in that regard, but the RMS amplitude was not as repeatable as desired, as is obvious from Table 4. This definitely had an effect on

both RMS error and the cross-adaptive instability level, for a larger-than-normal RMS input amplitude caused an increase in RMS error and a corresponding decrease in cross-adaptive instability levels, and vice-versa.

Another problem area arose from the fact that RMS errors were calculated during separate training runs and not during the tracking run itself (such as is done in Reference 4), for use as the criterion for the control of the secondary instability level. Any variance between runs in either operator adaptation, operator fatigue, or input amplitude contributed to a fluctuation in the raw cross-adaptive instability scores.

Fortunately, the effects of quantization were quite pronounced. Due to this fact the above problem areas were minor in their effect upon the results, but should be ocrrected for any future research.

V. CONCLUSIONS AND RECOMMENDATIONS

The following conclusions are drawn as a result of this research:

1. Display signal quantization has a definite effect upon operator effective time delay, the relationship being almost one of proportionality as quantization level is increased.

2. Display signal quantization has a definite effect upon operator workload, The workload is considerably greater with quantization than it is for the continuous display.

3. An extremely flexible hybrid computer scheme has been generated for both this research and for future research. All materials concerned (digital computer program, analog computer patchboard, etc.) are maintained in the Electrical Engineering Computer Laboratory, U.S. Naval Postgraduate School under the care of Asst. Professor R. A. Hess, Department of Aeronautics, U.S. Naval Postgraduate School. The digital program is being revised at the time of this writing to mechanize the cross-adaptive task in complete accordance with that suggested in Reference 4. All analog computer schematics are contained in this report.

4. The hybrid computer is an invaluable aid for the mechanization of compensatory tracking tasks, offering as it does the capability for both on-line and off-line data computation, as well as a

flexibility limited only by the digital computer's core storage capabilities and the analog computer's finite patchboard size.

No conclusions can be drawn concerning any "optimal" quantization interval.

The following recommendations are offered:

1. Continued development of the cross-adaptive task is clearly indicated. A starting point of note, however, seems to be the task proposed in Reference 4, wherein the RMS error which is used as a criterion for adjusting the secondary instability is computed during the actual run itself, yet prior to allowing the secondary instability to vary.

2. If an "optimal" quantization interval is to be discovered in future research, a reasonable value of initial interest could well be the 0.7257 quantization interval.

3. For displays in tasks which require any lead generation, no quantization should be used. The resulting operator workload and operator effective delay time deteriorations are unacceptable.

4. As a source of the input in compensatory tracking tasks, a random noise generator is unsatisfactory. A more precise and, more important, repeatable source is a sum of sine waves which, if used properly, appear random when presented to the operator.

APPENDIX A TABLES

AVAILABLE TRACKING TASKS	FIGURE NUMBER OF APPLICABLE BLOCK DIAGRAM	FIGURE NUMBER OF APPLICABLE ANALOG SCHEMATIC
FIRST ORDER SINGLE-AXIS CRITICAL	1	7
"1.5" ORDER SINGLE-AXIS CRITICAL		8
SECOND ORDER SINGLE-AXIS CRITICAL		9
FIRST ORDER DUAL-AXIS CRITICAL	2	10
"1.5" ORDER DUAL-AXIS CRITICAL		11
SECOND ORDER DUAL-AXIS CRITICAL		12
FIRST ORDER CROSS-ADAPTIVE	3	13
"1.5" ORDER CROSS-ADAPTIVE		14
SECOND ORDER CROSS-ADAPTIVE		15
FIRST ORDER SINGLE-AXIS SUBCRITICAL	4	16
"1.5" ORDER SINGLE-AXIS SUBCRITICAL		17
SECOND ORDER SINGLE-AXIS SUBCRITICAL		18
FIRST ORDER DUAL-AXIS SUBCRITICAL	5	19
"1.5" ORDER DUAL-AXIS SUBCRITICAL		20
SECOND ORDER DUAL-AXIS SUBCRITICAL		21

TABLE I PROGRAMMED TRACKING TASK TYPES

SUBJECT RH						
QUANTIZATION INTERVAL (cm)	INSTABILITY LEVELS (rad/sec)					
	Ist ORDER		"1.5" ORDER		2nd ORDER	
	$\overline{\lambda_c}$	SD	$\overline{\lambda_c}$	SD	$\overline{\lambda_c}$	SD
0	6.11	0.22	4.39	0.15	3.46	0.12
0.0635	5.44	0.28	4.17	0.14	3.35	0.16
0.2540	5.25	0.16	4.02	0.26	3.06	0.11
0.5080	4.96	0.14	3.76	0.14	2.72	0.10
0.7257	5.12	0.14	3.50	0.15	2.59	0.21
1.0160	4.73	0.17	3.14	0.10	2.60	0.25
1.2700	4.28	0.09	3.25	0.10	-	-
1.6933	4.23	0.16	2.77	0.19	-	-

SUBJECT WT						
QUANTIZATION INTERVAL (cm)	INSTABILITY LEVELS (rad/sec)					
	Ist ORDER		"1.5" ORDER		2nd ORDER	
	$\overline{\lambda_c}$	SD	$\overline{\lambda_c}$	SD	$\overline{\lambda_c}$	SD
0	6.70	0.32	4.79	0.20	3.75	0.11
0.0635	6.50	0.14	4.50	0.13	3.45	0.06
0.2540	6.12	0.19	4.30	0.16	3.19	0.03
0.5080	5.79	0.19	3.94	0.18	2.97	0.09
0.7257	5.80	0.20	3.67	0.22	2.70	0.09
1.0160	5.48	0.18	3.50	0.05	2.28	0.07
1.2700	5.16	0.27	3.36	0.10	-	-
1.6933	4.82	0.12	3.17	0.20	-	-

TABLE 2 SINGLE-AXIS CRITICAL INSTABILITY LEVELS

SUBJECT RH						
QUANTIZATION INTERVAL (cm)	INSTABILITY LEVELS (rad/sec)					
	1st ORDER		"1.5" ORDER		2nd ORDER	
	$\overline{\lambda_D}$	SD	$\overline{\lambda_D}$	SD	$\overline{\lambda_D}$	SD
0	4.89	0.11	3.48	0.10	2.83	0.11
0.0635	4.69	0.09	3.51	0.25	2.78	0.11
0.2540	4.52	0.15	3.06	0.06	2.46	0.16
0.5080	4.37	0.19	2.88	0.14	2.11	0.13
0.7257	4.32	0.06	2.54	0.11	-	-
1.0160	3.80	0.15	2.43	0.07	-	-
1.2700	3.24	0.10	-	-	-	-
1.6933	3.26	0.06	-	-	-	-

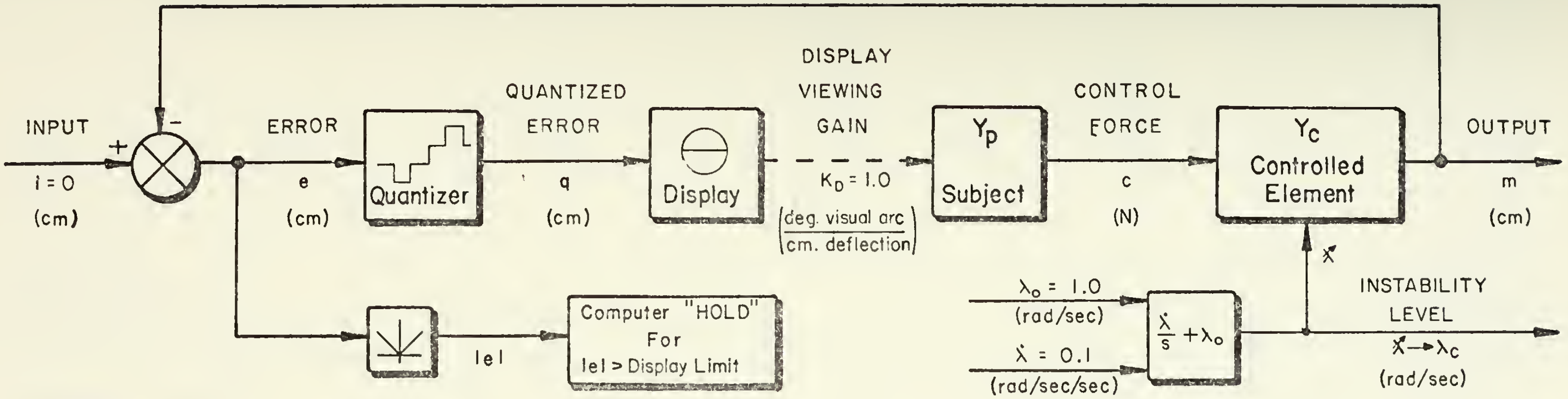
SUBJECT WT						
QUANTIZATION INTERVAL (cm)	INSTABILITY LEVELS (rad/sec)					
	1st ORDER		"1.5" ORDER		2nd ORDER	
	$\overline{\lambda_D}$	SD	$\overline{\lambda_D}$	SD	$\overline{\lambda_D}$	SD
0	5.42	0.07	4.15	0.10	3.02	0.06
0.0635	5.31	0.07	3.77	0.04	2.82	0.05
0.2540	5.25	0.07	3.60	0.06	2.50	0.04
0.5080	4.90	0.09	3.00	0.08	2.22	0.02
0.7257	4.84	0.10	2.76	0.03	-	-
1.0160	4.65	0.11	2.60	0.08	-	-
1.2700	4.32	0.11	-	-	-	-
1.6933	4.04	0.22	-	-	-	-

TABLE 3 DUAL-AXIS CRITICAL INSTABILITY LEVELS

	QUANTIZATION INTERVAL (cm)	TRAINING RUNS				CROSS-ADAPTIVE TRACKING RUNS					
		RMS INPUT (cm)		RMS ERROR (cm)		RMS INPUT (cm)		RMS ERROR (cm)		INSTABILITY LEVEL (rad/sec)	
		$\overline{i_{rms}}$	SD	$\overline{e_{rms}}$	SD	$\overline{i_{rms}}$	SD	$\overline{e_{rms}}$	SD	$\overline{\lambda_x}$	SD
1st ORDER	0	1.041	0.021	0.545	0.016	1.008	0.086	0.602	0.023	4.66	0.27
	0.5080	0.995	0.069	0,572	0.020	1.053	0.060	0.642	0.013	3.26	0.18
"1.5" ORDER	0	0.514	0.023	0,378	0.009	0.548	0.024	0.415	0.013	3.86	0.18
	0.2540	0.507	0.048	0.403	0.011	0.535	0.038	0.475	0.018	2.26	0.30
2nd ORDER	0	0.497	0.020	0.583	0.030	0.521	0.017	0.706	0.038	2.54	0.22
	0.2540	0.504	0.031	0.602	0.012	0.518	0.023	0.729	0.039	2.02	0.30

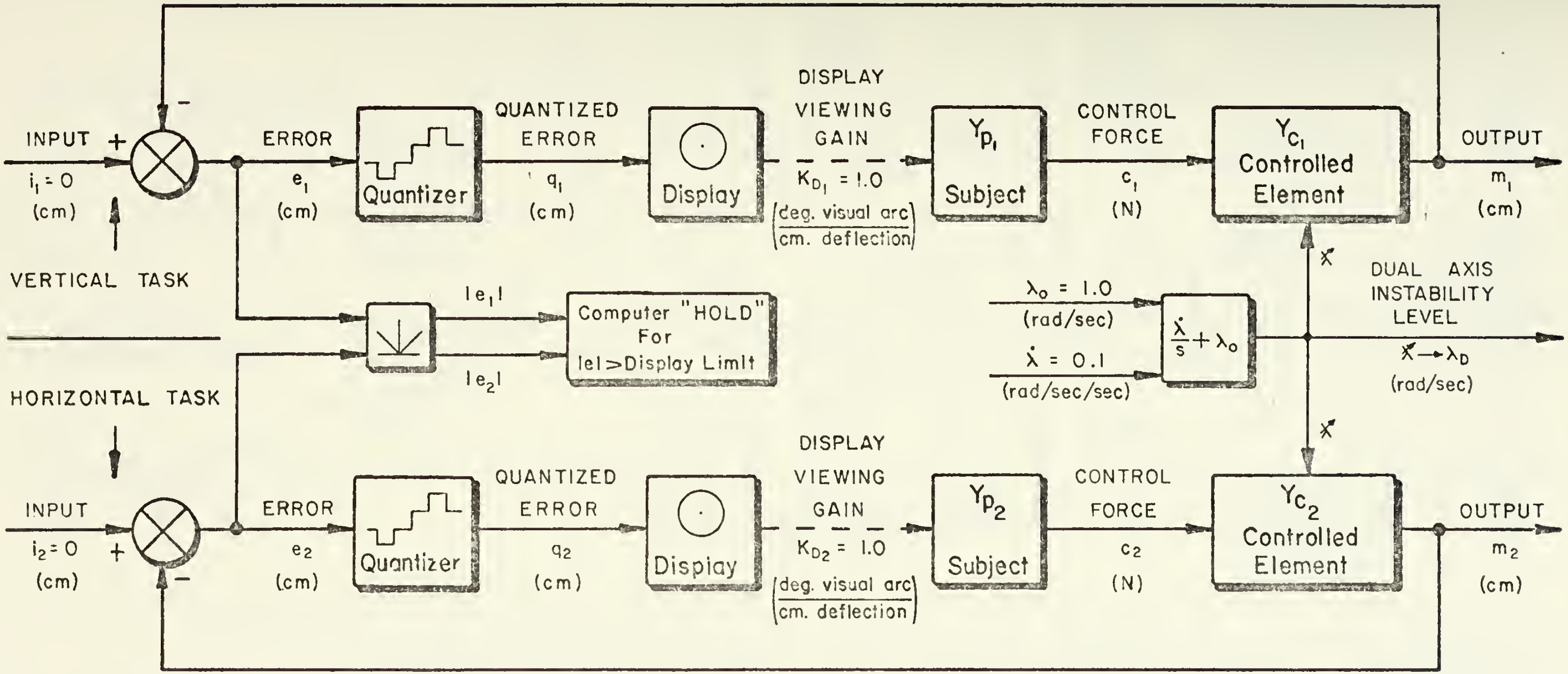
TABLE 4 CROSS-ADAPTIVE TRACKING TASK RESULTS

APPENDIX B FIGURES



SINGLE-AXIS CRITICAL TRACKING TASK PARAMETERS			
	1st ORDER	"1.5" ORDER	2nd ORDER
Y_c = CONTROLLED ELEMENT	$\frac{K_c\lambda}{s-\lambda}$	$\frac{K_c\lambda}{(s+2)(s-\lambda)}$	$\frac{K_c\lambda}{s(s-\lambda)}$
K_c = CONTROL SENSITIVITY	1.0 (cm/N)	3.33 (cm/sec/N)	3.33 (cm/sec/N)

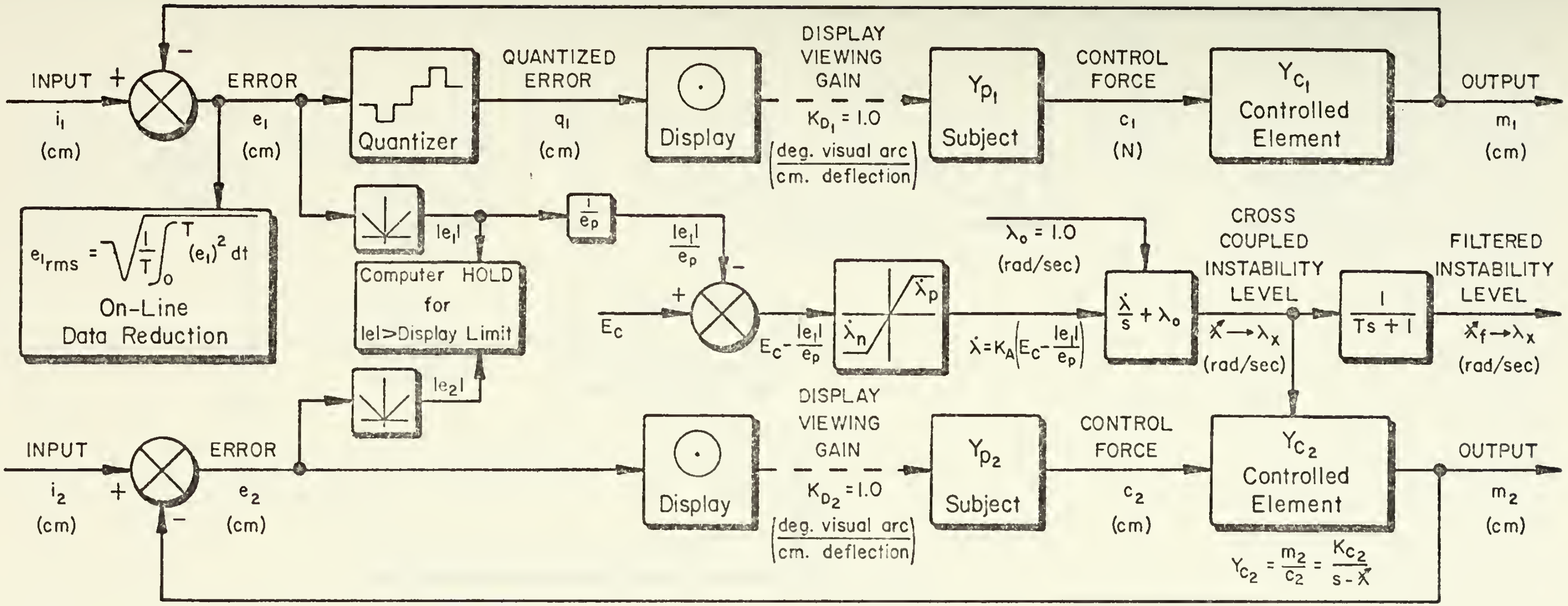
FIGURE 1 BLOCK DIAGRAM OF A SINGLE-AXIS CRITICAL TASK



DUAL-AXIS CRITICAL TRACKING TASK PARAMETERS

	1st ORDER	"1.5" ORDER	2nd ORDER
Y_{C_1} = VERTICAL CONTROLLED ELEMENT Y_{C_2} = HORIZONTAL CONTROLLED ELEMENT	$\frac{K_C \lambda}{s - \lambda}$	$\frac{K_C \lambda}{(s+2)(s-\lambda)}$	$\frac{K_C \lambda}{s(s-\lambda)}$
K_{C_1} = VERTICAL CONTROL SENSITIVITY K_{C_2} = HORIZONTAL CONTROL SENSITIVITY	1.0 (cm/N)	3.33 (cm/sec/N)	3.33 (cm/sec/N)

FIGURE 2 BLOCK DIAGRAM OF A DUAL-AXIS CRITICAL TASK



	1st ORDER	"1.5" ORDER	2nd ORDER
INPUT RMS AMPLITUDE	1.0 cm	0.5 cm	
INPUT BANDWIDTH	2.0 rad/sec		
K_{c_1} = CONTROL SENSITIVITY	1.0 cm/N	3.33 cm/sec/N	
K_{c_2} = CONTROL SENSITIVITY	1.0 cm/N		
Y_{c_1} = PRIMARY TASK CONTROLLED ELEMENT	$\frac{K_{c_1}}{s}$	$\frac{K_{c_1}}{s(s+2)}$	$\frac{K_{c_1}}{s^2}$

e_p = RMS error established on a previous run during which the secondary task instability level was constant at 1.0 rad/sec

E_c = ERROR CRITERION = 1.0

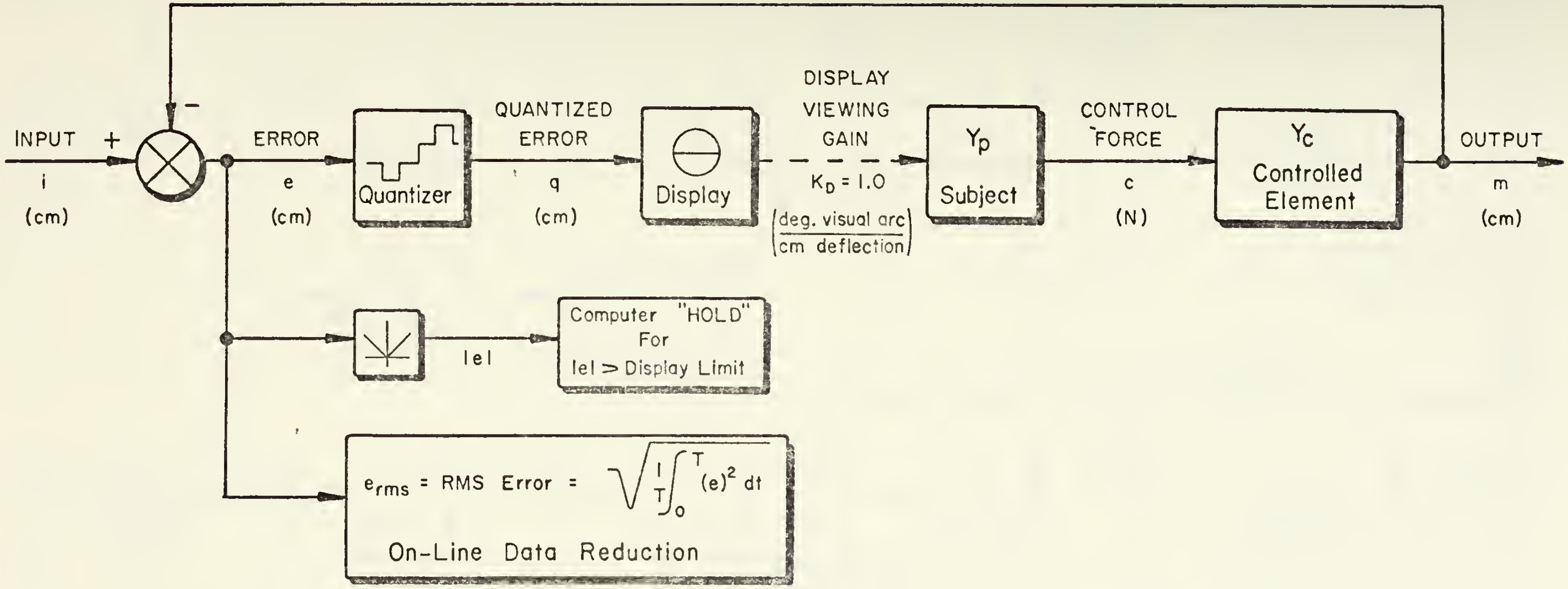
$\dot{\lambda}_p$ = maximum rate of increase of λ = 0.15 rad/sec/sec

$\dot{\lambda}_n$ = maximum rate of decrease of λ = 0.30 rad/sec/sec

K_A = 0.40 rad/sec/sec

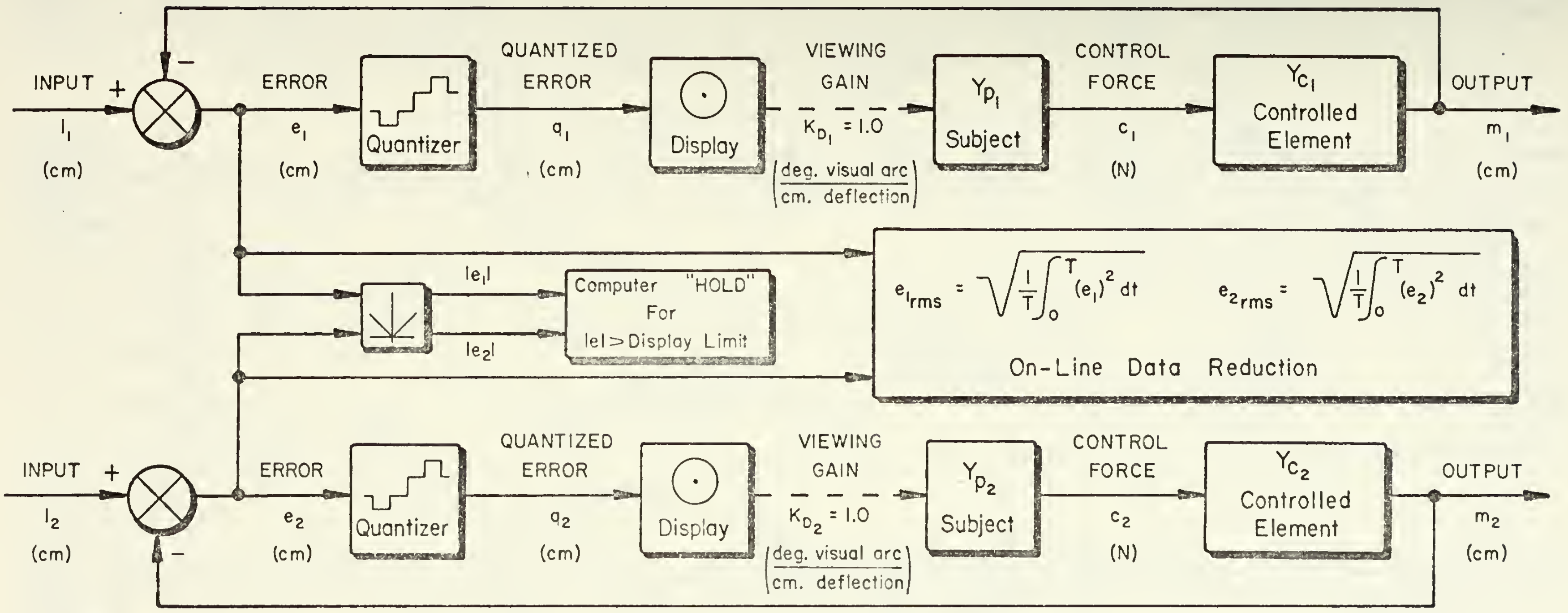
T = SMOOTHING FILTER TIME CONSTANT = 10 seconds

FIGURE 3 BLOCK DIAGRAM OF A CROSS-ADAPTIVE TASK



SINGLE-AXIS SUBCRITICAL TRACKING TASK PARAMETERS			
	1st ORDER	"1.5" ORDER	2nd ORDER
INPUT RMS AMPLITUDE	1.0 cm	0.5 cm	
INPUT BANDWIDTH	2.0 rad/sec		
Y_c = CONTROLLED ELEMENT	$\frac{K_c}{s}$	$\frac{K_c}{s(s+2)}$	$\frac{K_c}{s^2}$
K_c = CONTROL SENSITIVITY	1.0 cm/N	3.33 cm/sec/N	

FIGURE 4 BLOCK DIAGRAM OF A SINGLE-AXIS SUBCRITICAL TASK



DUAL-AXIS SUBCRITICAL TRACKING TASK PARAMETERS			
	1st ORDER	"1.5" ORDER	2nd ORDER
VERTICAL & HORIZONTAL INPUT RMS AMPLITUDE	1.0 cm	0.5 cm	
VERTICAL & HORIZONTAL INPUT BANDWIDTH	2.0 rad/sec		
VERTICAL & HORIZONTAL CONTROLLED ELEMENT	$\frac{K_c}{s}$	$\frac{K_c}{s(s+2)}$	$\frac{K_c}{s^2}$
K_{c_1} & K_{c_2} = CONTROL SENSITIVITIES	1.0 cm/N	3.33 cm/sec/N	

FIGURE 5 BLOCK DIAGRAM OF A DUAL-AXIS SUBCRITICAL TASK

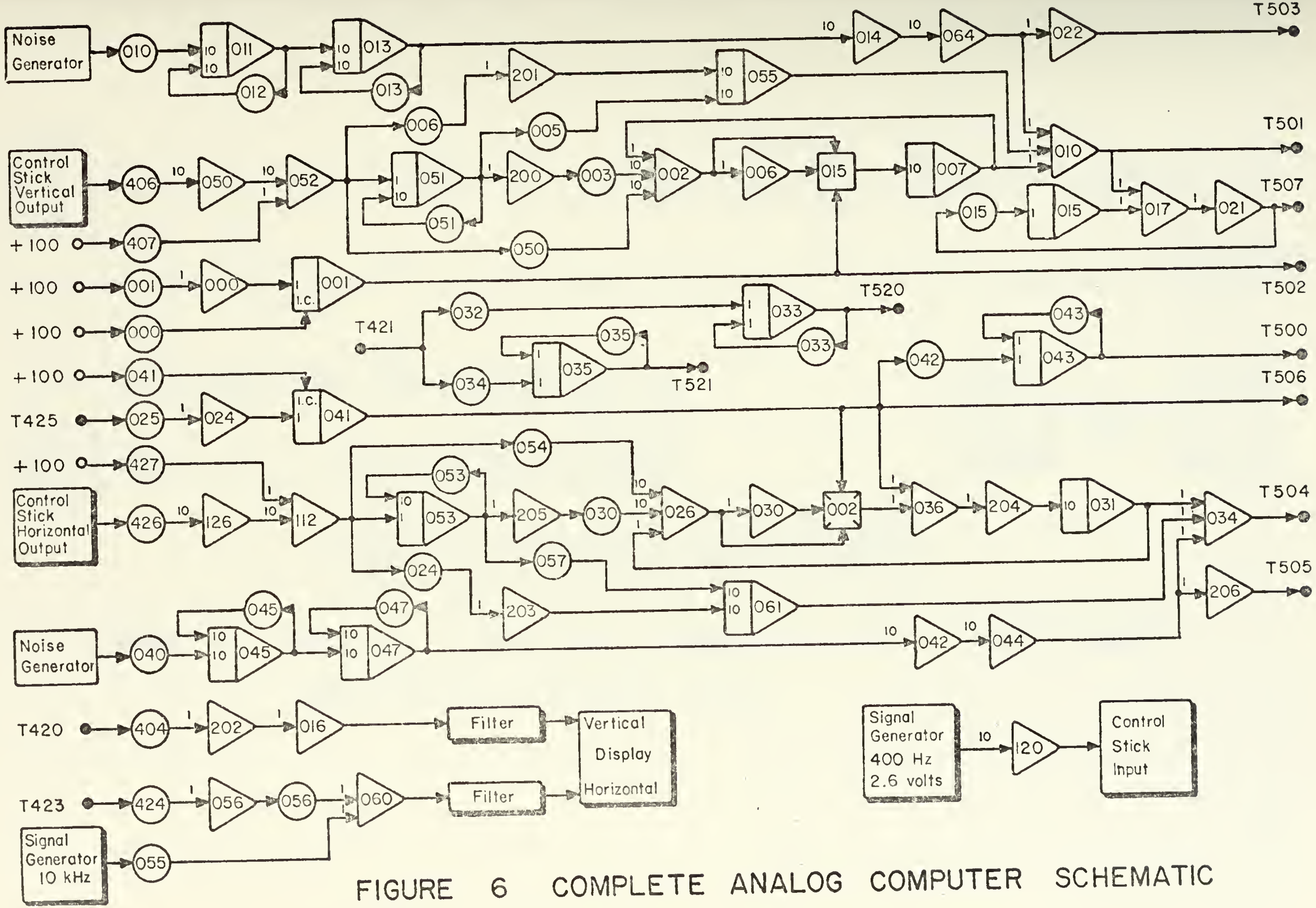
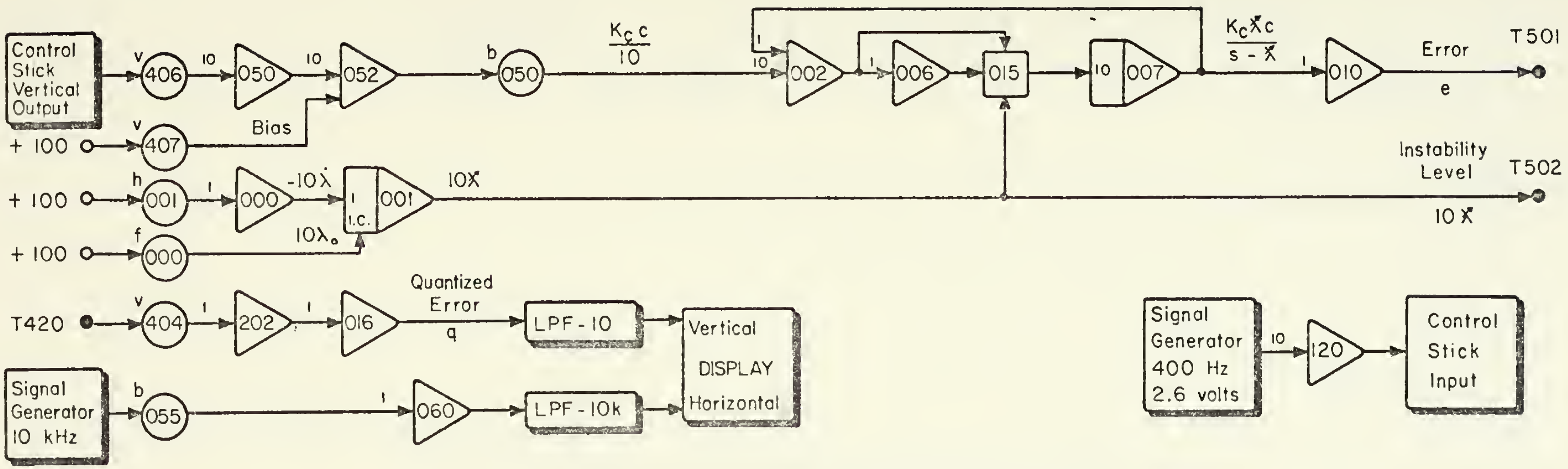
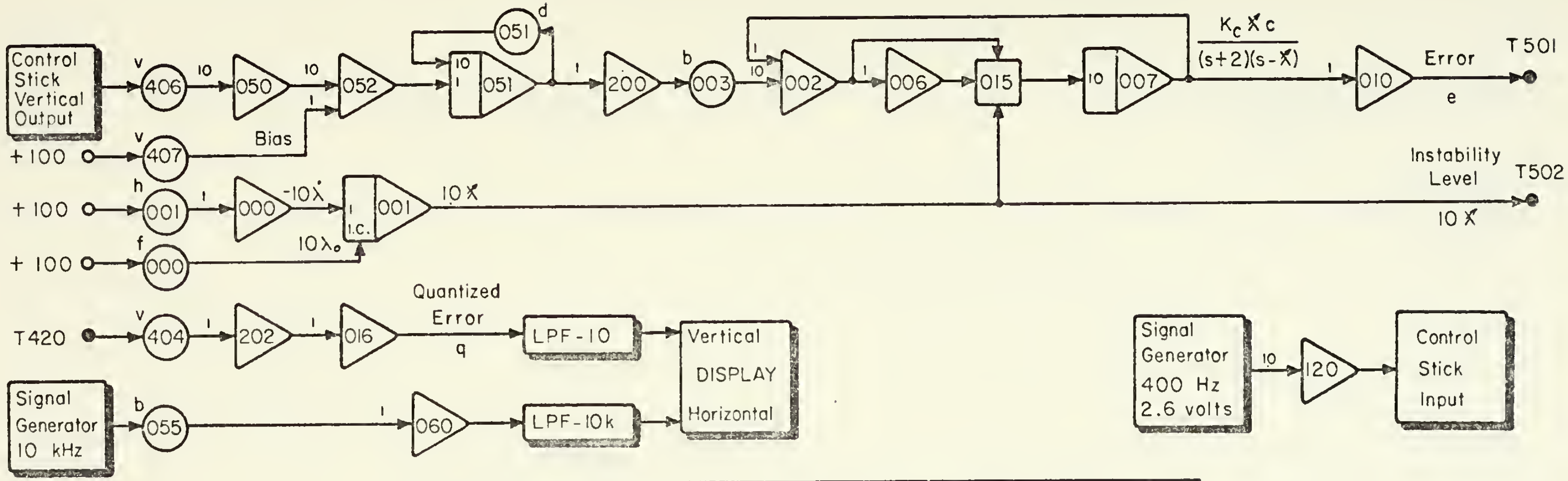


FIGURE 6 COMPLETE ANALOG COMPUTER SCHEMATIC



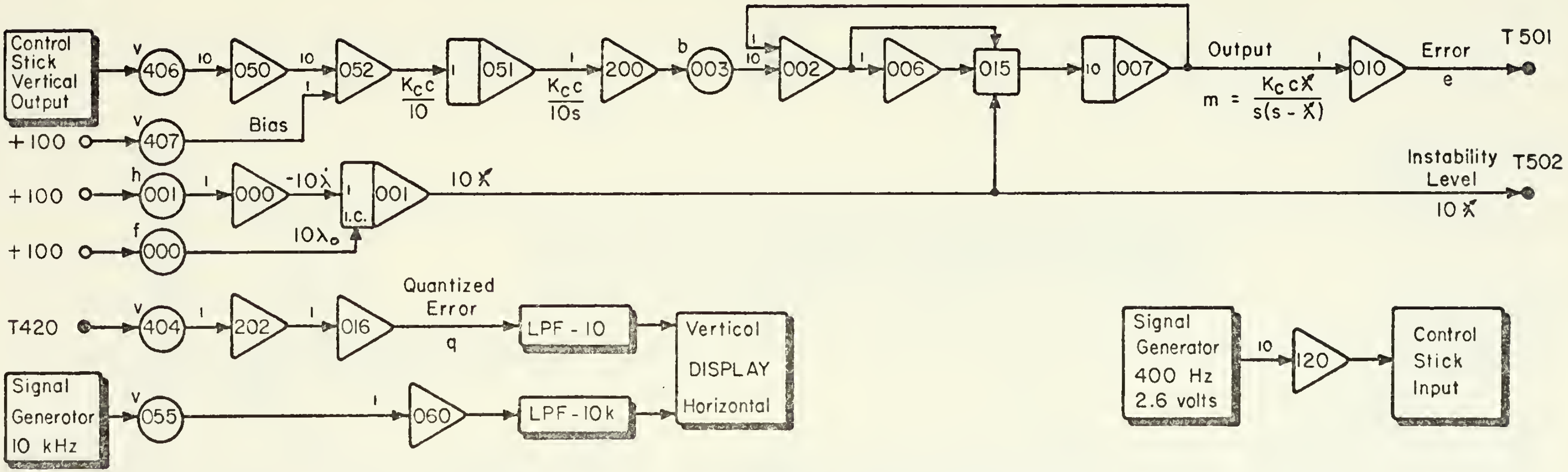
Potentiometer Settings	v = as needed for stick/display calibration		
	b = 0.9999	f = 0.1000	h = 0.0100

FIGURE 7 ANALOG COMPUTER SCHEMATIC FOR A FIRST ORDER SINGLE-AXIS CRITICAL TASK



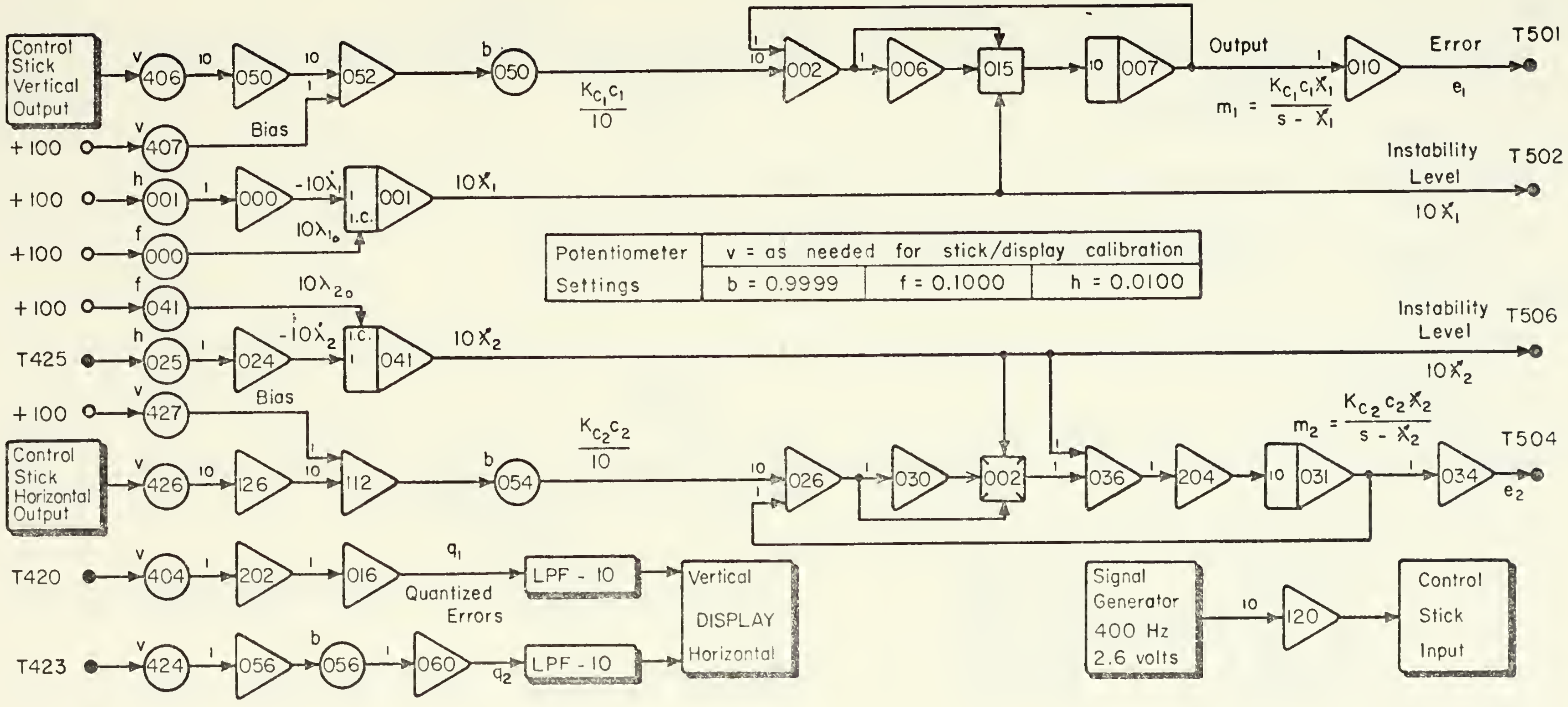
Potentiometer Settings	v = as needed for stick/display calibration			
	b = 0.9999	d = 0.2000	f = 0.1000	h = 0.0100

FIGURE 8 ANALOG COMPUTER SCHEMATIC FOR A "1.5" ORDER SINGLE-AXIS CRITICAL TASK



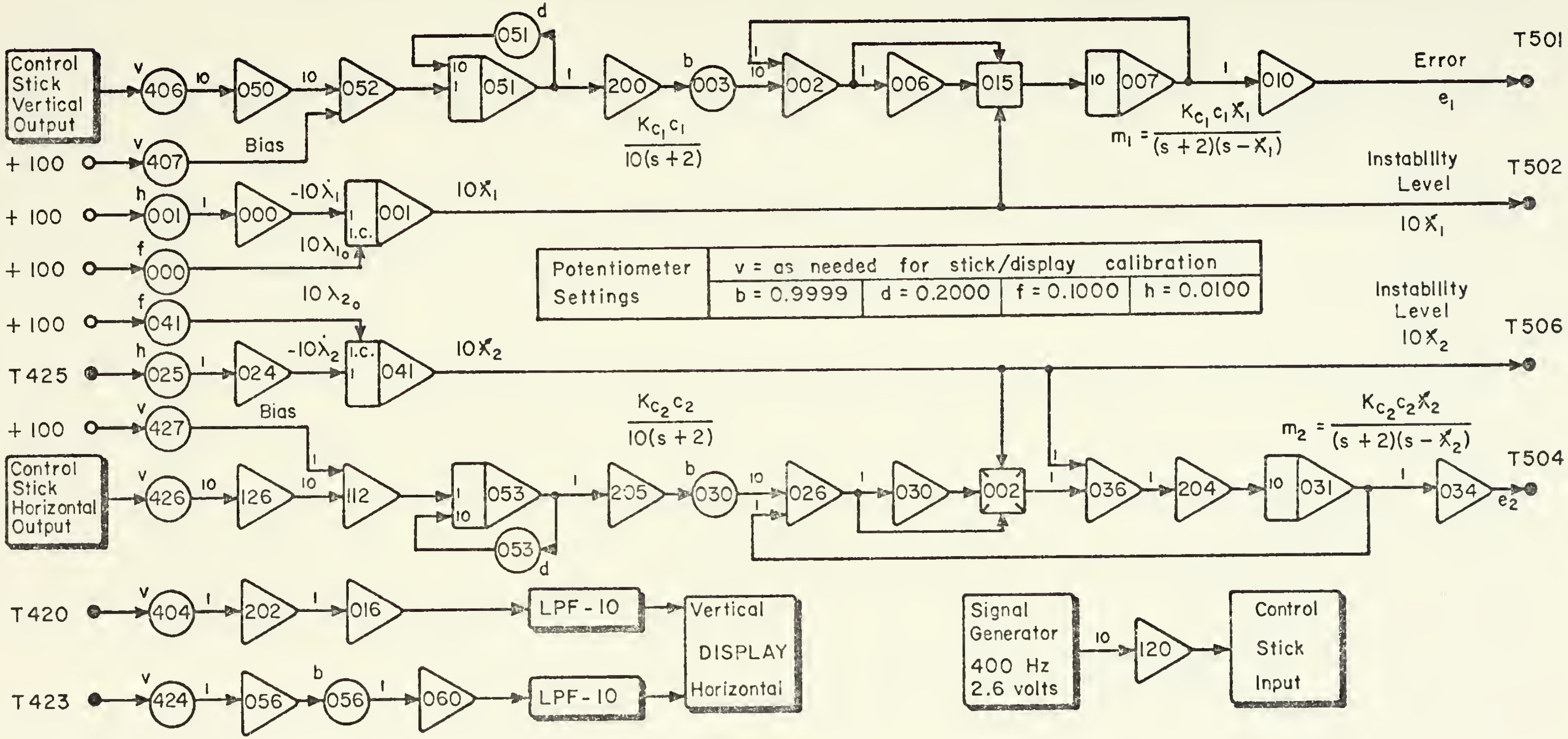
Potentiometer Settings	v = as needed for stick/display calibration		
	b = 0.9999	f = 0.1000	h = 0.0100

FIGURE 9 ANALOG COMPUTER SCHEMATIC FOR A SECOND ORDER SINGLE-AXIS CRITICAL TASK



Potentiometer Settings	v = as needed for stick/display calibration		
	b = 0.9999	f = 0.1000	h = 0.0100

FIGURE 10 ANALOG COMPUTER SCHEMATIC FOR A FIRST ORDER DUAL-AXIS CRITICAL TASK



Potentiometer Settings	v = as needed for stick/display calibration			
	b = 0.9999	d = 0.2000	f = 0.1000	h = 0.0100

FIGURE 11 ANALOG COMPUTER SCHEMATIC FOR A "1.5" ORDER DUAL-AXIS CRITICAL TASK

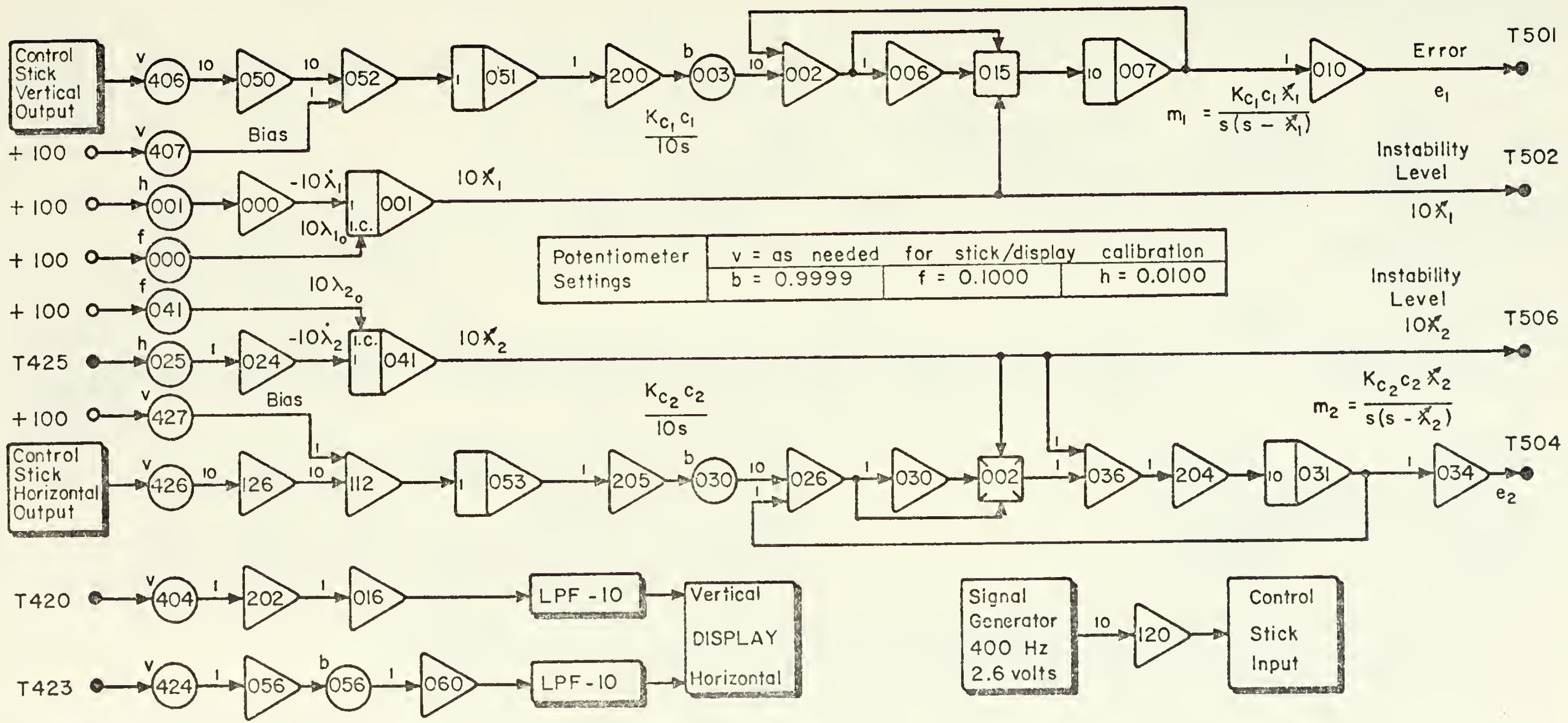
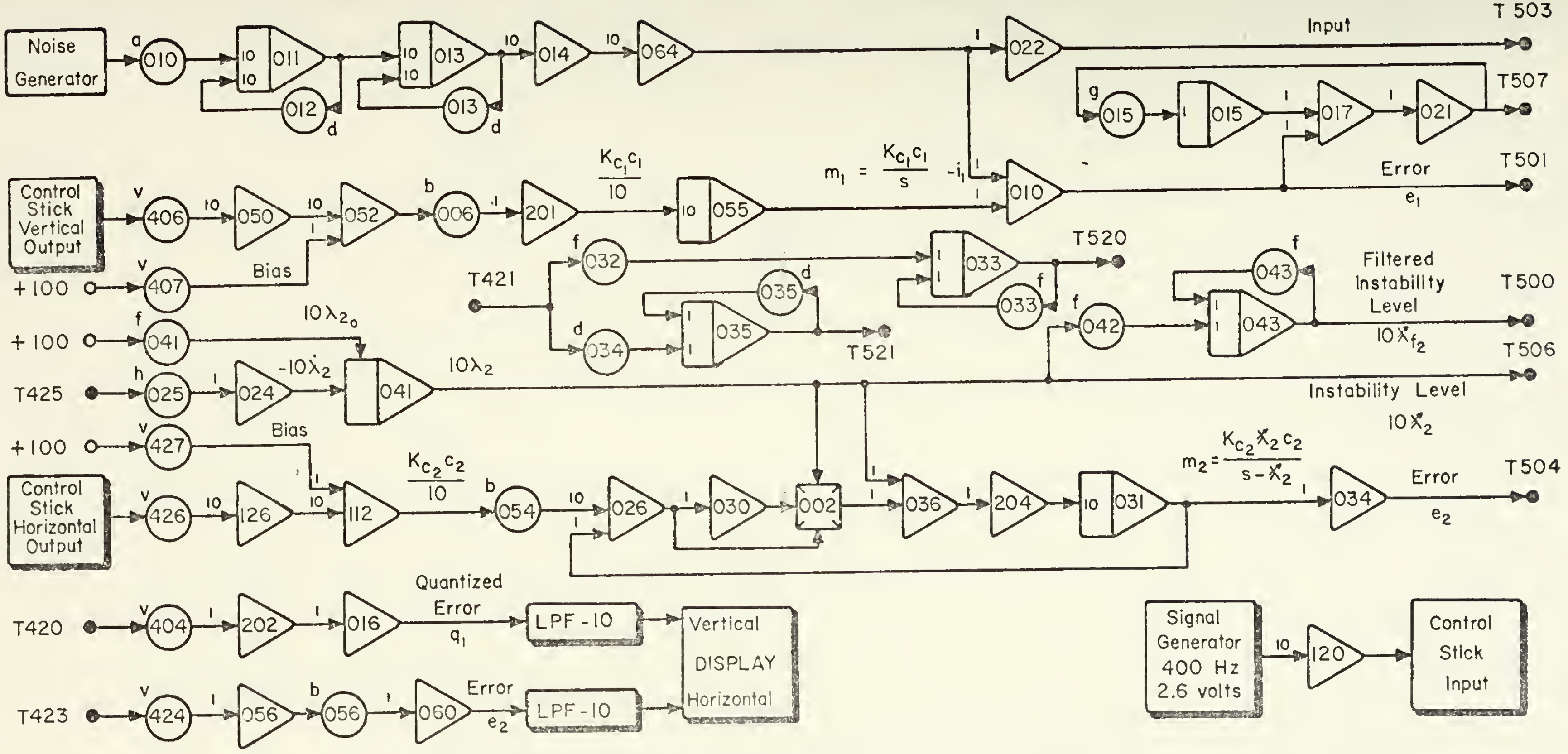
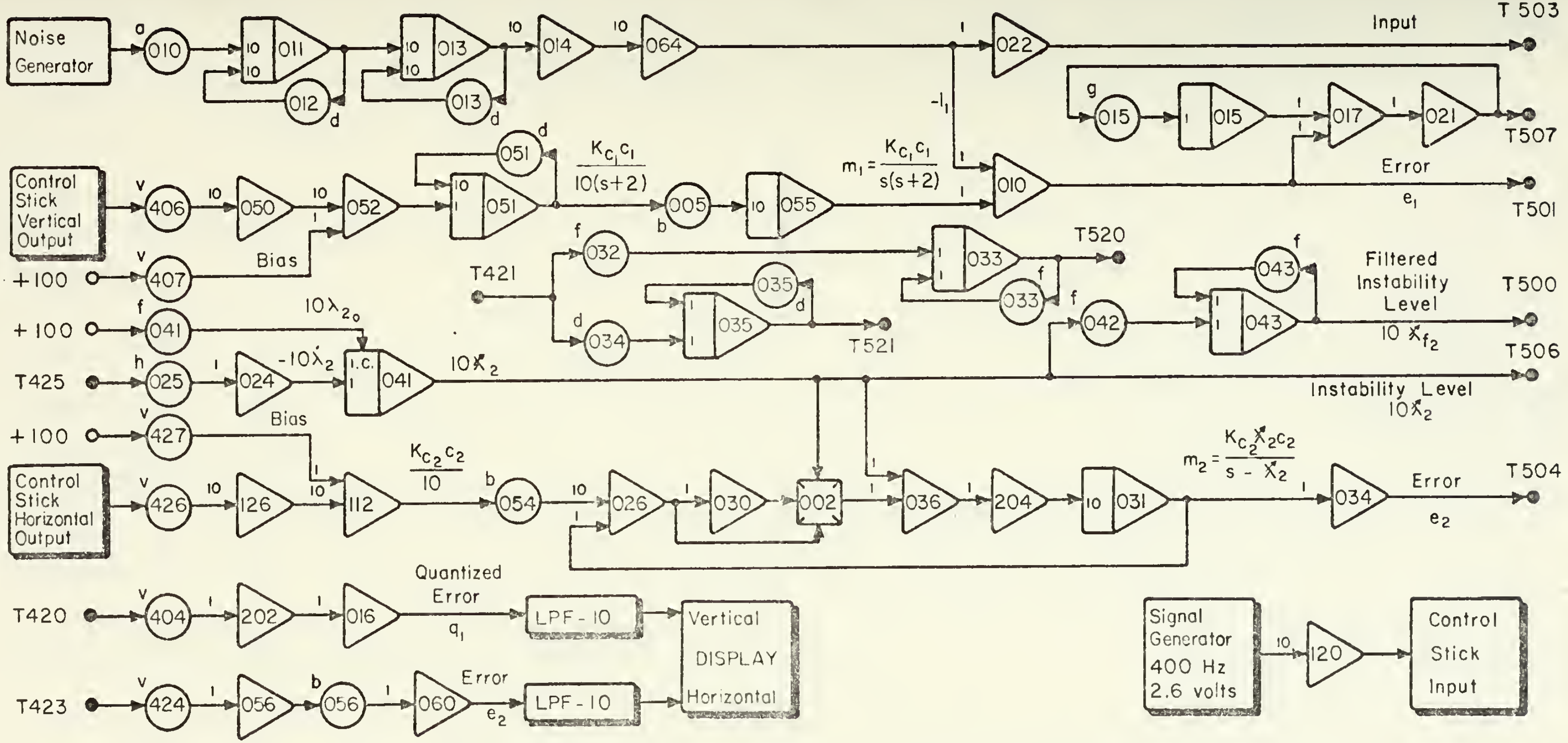


FIGURE 12 ANALOG COMPUTER SCHEMATIC FOR A SECOND ORDER DUAL-AXIS CRITICAL TASK



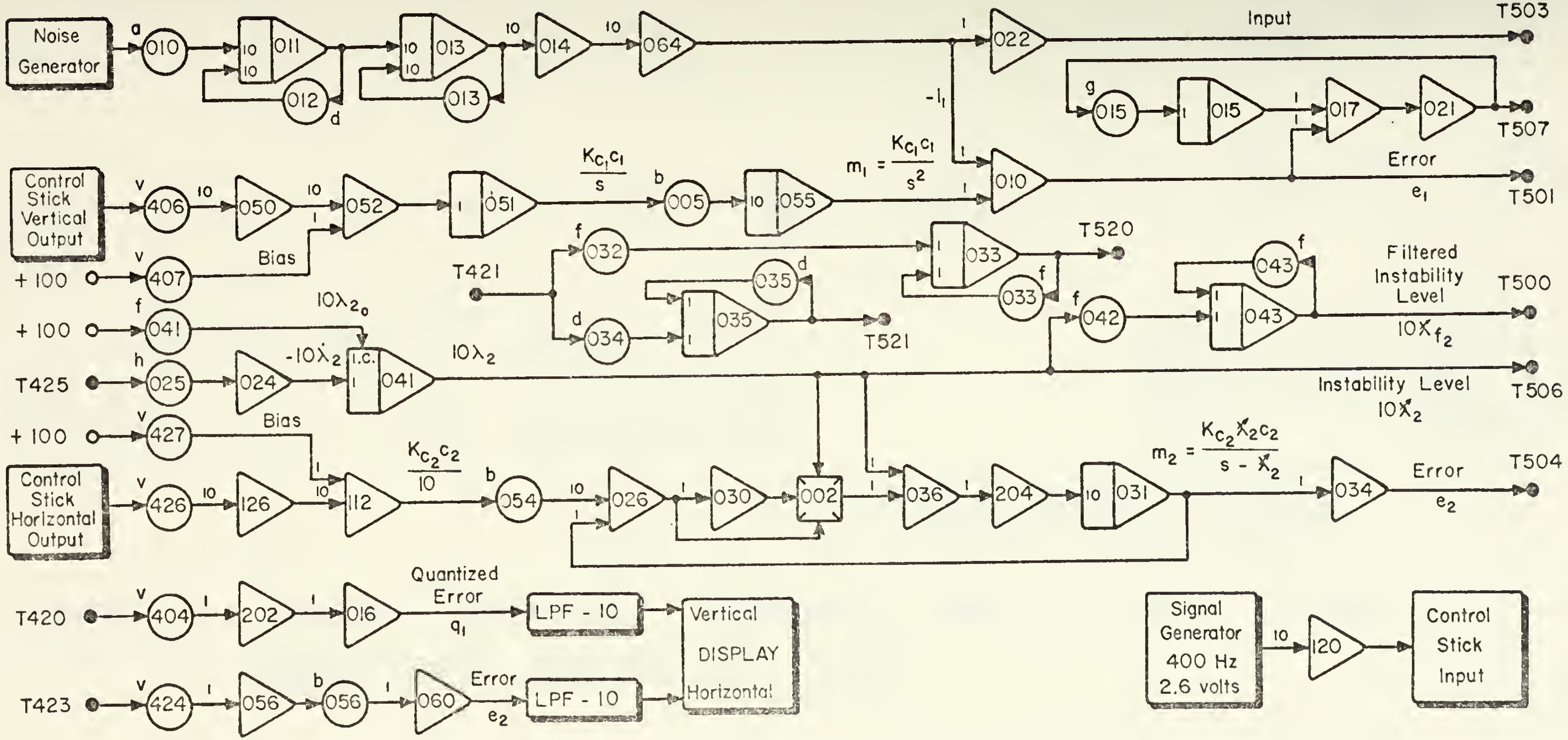
Potentiometer Settings	v = as needed for stick/display calibration					
	a = 0.2340	b = 0.9999	d = 0.2000	f = 0.1000	h = 0.0100	g = 0.5000

FIGURE 13 ANALOG COMPUTER SCHEMATIC FOR A FIRST ORDER CROSS-ADAPTIVE TASK



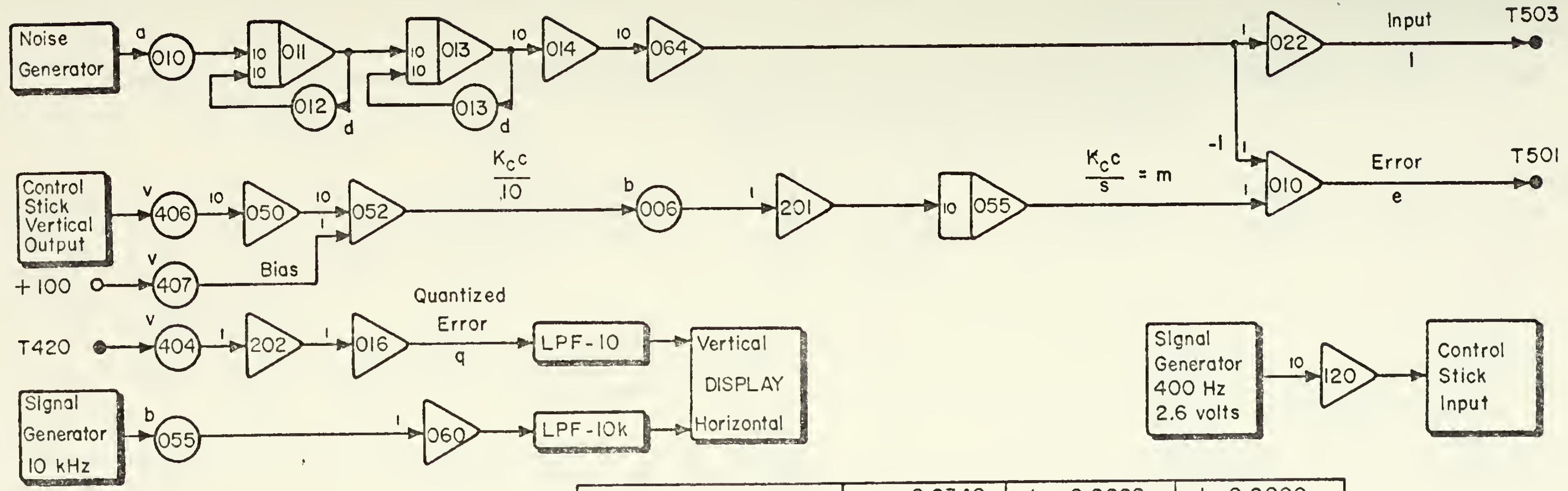
Potentiometer Settings	v = as needed for stick/display calibration					
	a = 0.1170	b = 0.9999	d = 0.2000	f = 0.1000	h = 0.0100	g = 0.5000

FIGURE 14 ANALOG COMPUTER SCHEMATIC FOR A "1.5" ORDER CROSS-ADAPTIVE TASK



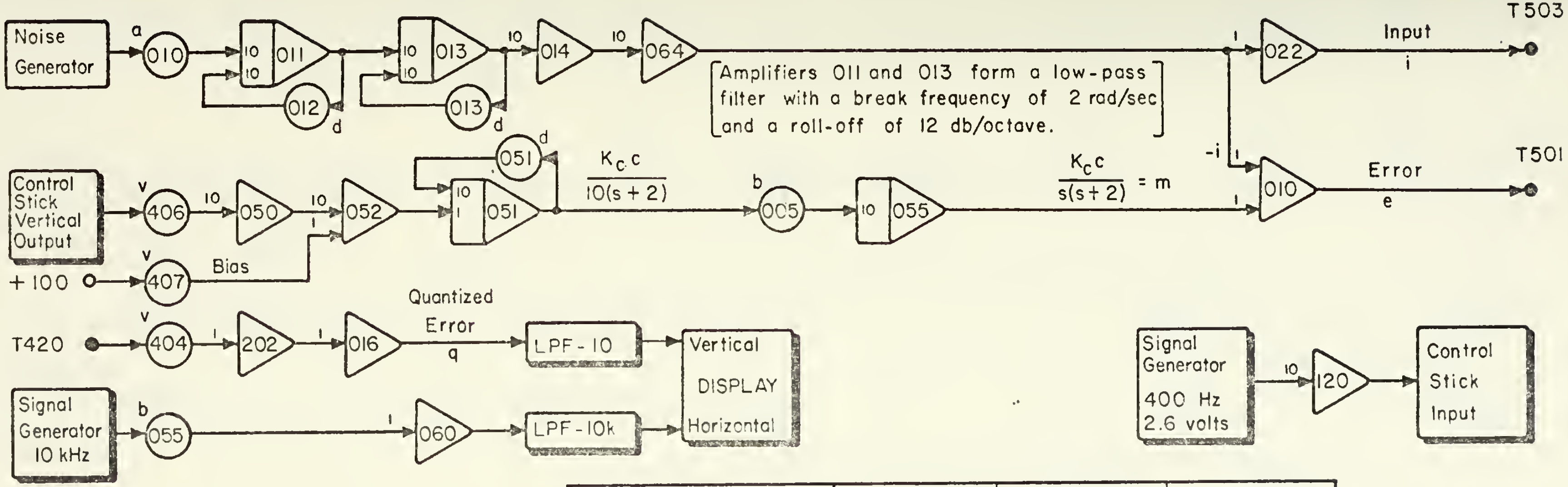
Potentiometer Settings	v = as needed for stick/display calibration				g = 0.5000
	a = 0.1170	b = 0.9999	d = 0.2000	f = 0.1000	h = 0.0100

FIGURE 15 ANALOG COMPUTER SCHEMATIC FOR A SECOND ORDER CROSS-ADAPTIVE TASK



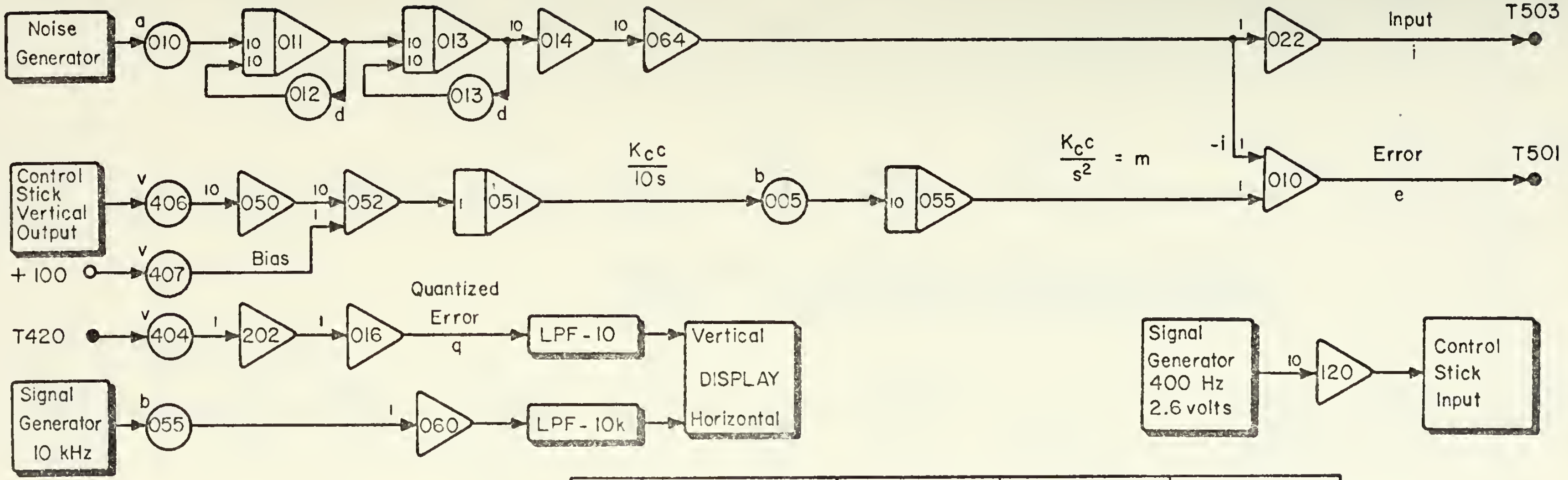
Potentiometer Settings	a = 0.2340	b = 0.9999	d = 0.2000
	v = as needed for stick/display calibration		

FIGURE 16 ANALOG COMPUTER SCHEMATIC FOR A FIRST ORDER SINGLE-AXIS SUBCRITICAL TASK



Potentiometer Settings	a = 0.1170	b = 0.9999	d = 0.2000
	v = as needed for stick/display calibration		

FIGURE 17 ANALOG COMPUTER SCHEMATIC FOR A "1.5" ORDER SINGLE-AXIS SUBCRITICAL TASK



Potentiometer Settings	a = 0.1170	b = 0.9999	d = 0.2000
	v = as needed for stick/display calibration		

FIGURE 18 ANALOG COMPUTER SCHEMATIC FOR A SECOND ORDER SINGLE-AXIS SUBCRITICAL TASK

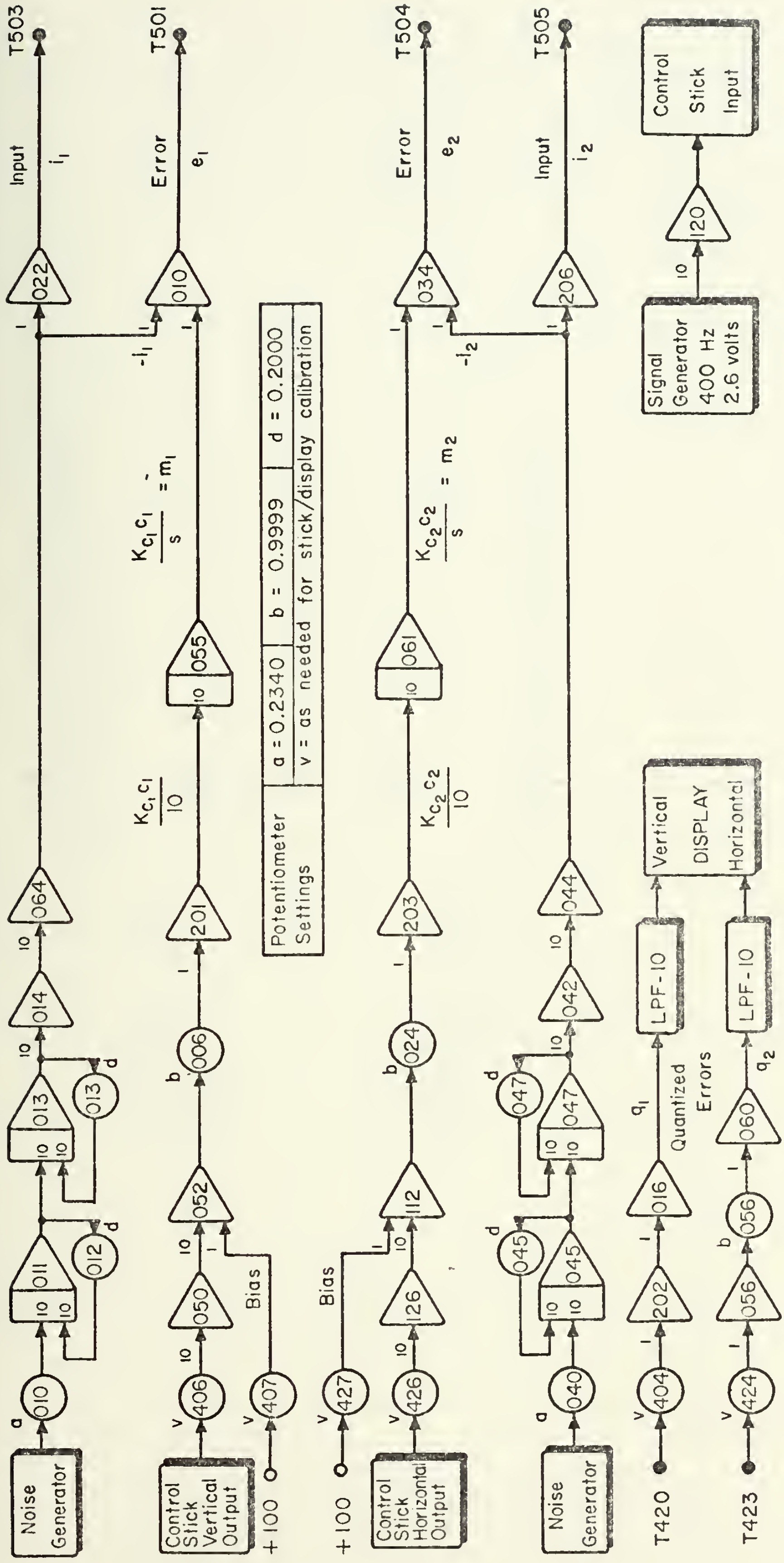
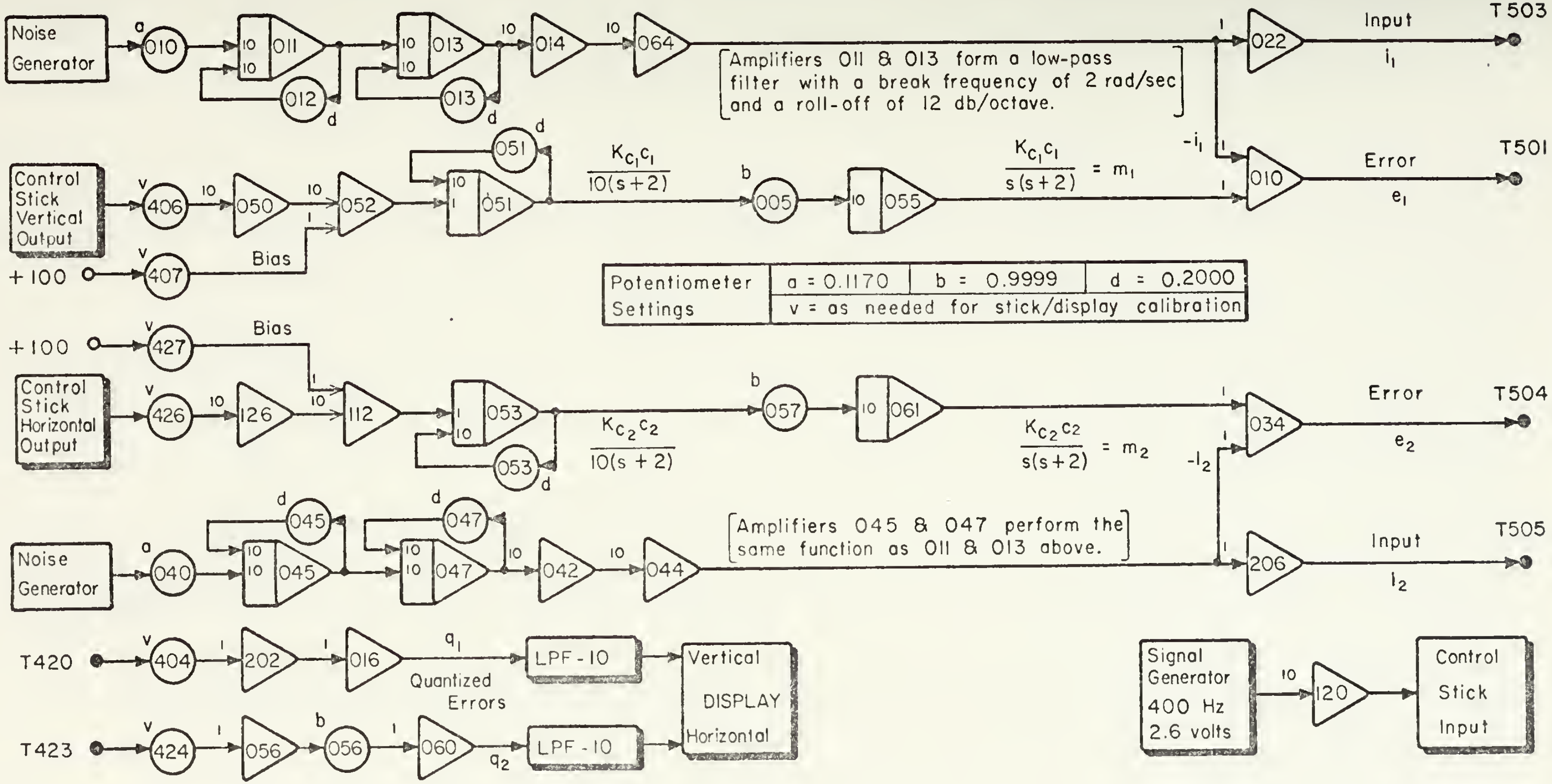


FIGURE 19 ANALOG COMPUTER SCHEMATIC FOR A FIRST ORDER DUAL-AXIS SUBCRITICAL TASK

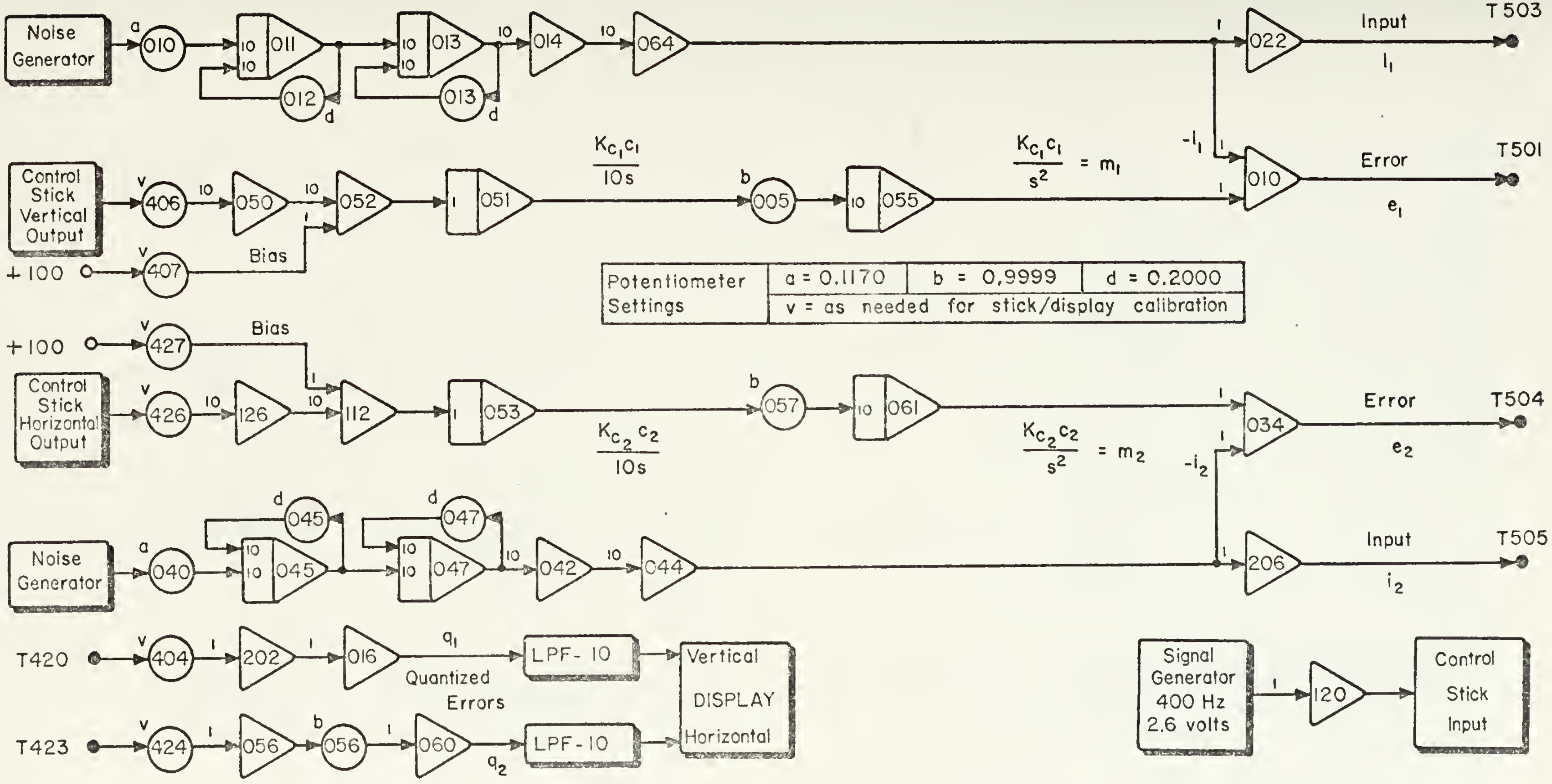


[Amplifiers 011 & 013 form a low-pass filter with a break frequency of 2 rad/sec and a roll-off of 12 db/octave.]

Potentiometer Settings	a = 0.1170	b = 0.9999	d = 0.2000
	v = as needed for stick/display calibration		

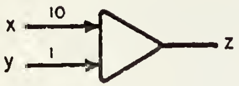
[Amplifiers 045 & 047 perform the same function as 011 & 013 above.]

FIGURE 20 ANALOG COMPUTER SCHEMATIC FOR A "1.5" ORDER DUAL-AXIS SUBCRITICAL TASK



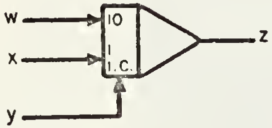
Potentiometer Settings	a = 0.1170	b = 0,9999	d = 0.2000
	v = as needed for stick/display calibration		

FIGURE 21 ANALOG COMPUTER SCHEMATIC FOR A SECOND ORDER DUAL-AXIS SUBCRITICAL TASK



Amplifier:

$z = -(10x + y)$



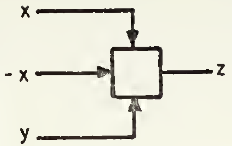
Integrating Amplifier:

$z = y - \int (10w + x)\,dt$

Low-Pass Filter:
Break Frequency at
(as shown) 10 Hz

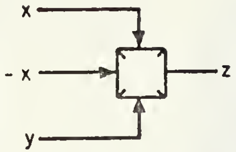
Shaded Boxes Indicate
Equipment External to
Analog Computer

Reference Voltage:
\+ or − 100 volts



Multiplier:

$z = -\frac{xy}{100}$



Multiplier:

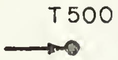
$z = -\frac{xy}{100} - x$

Potentiometer:

$z = ax$

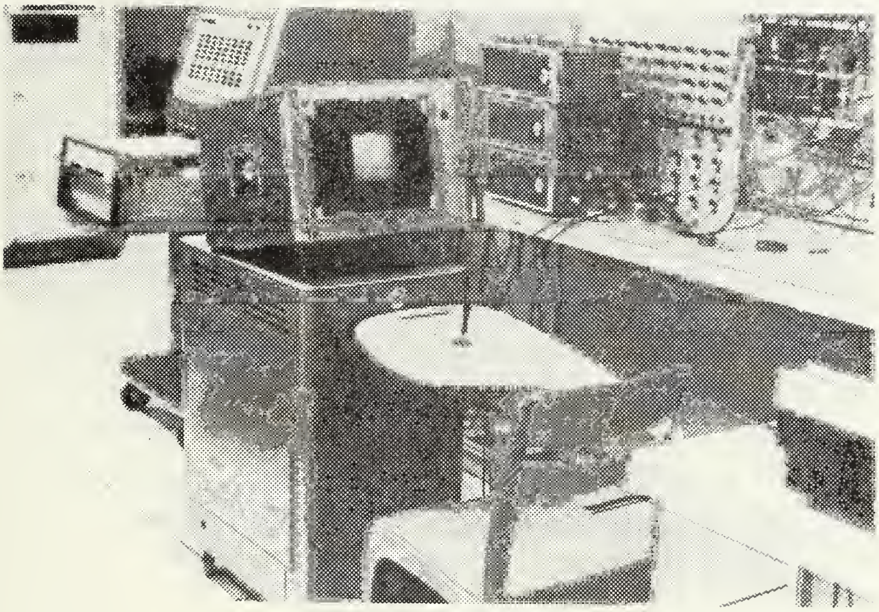
$(0 < a < 1.0)$

Trunk Line from Digital Computer
(400 Series)



Trunk Line to Digital Computer
(500 Series)

FIGURE 22 KEY TO SYMBOLS USED IN ANALOG COMPUTER SCHEMATICS (FIGURES 6 - 21)



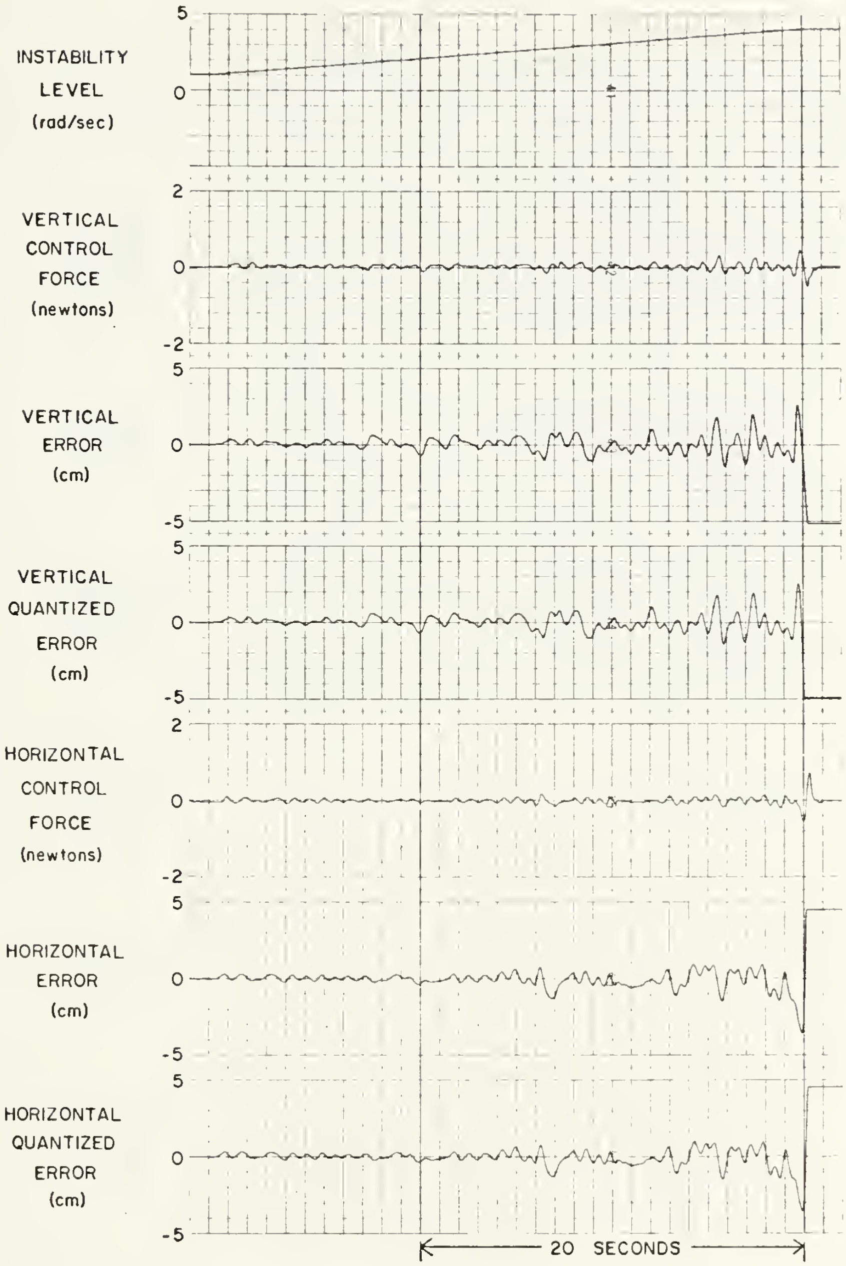
a) The Equipment

b) The Equipment in Use During a Tracking Run

FIGURE 23 TRACKING TASK EQUIPMENT

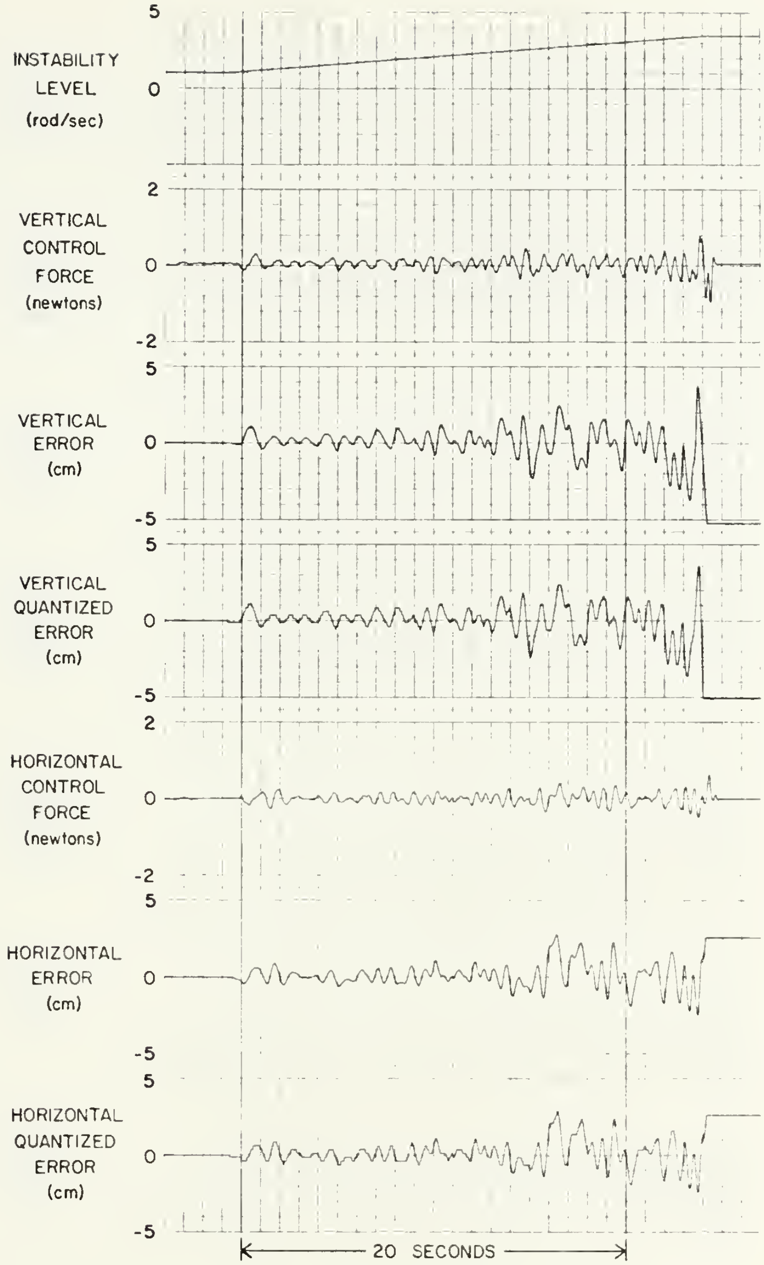
[illegible]

[illegible]



SIGN CONVENTION
Positive vertical control force = Control stick aft
Positive horizontal control force = Control stick right
Positive vertical error = Up on display
Positive horizontal error = Right on display

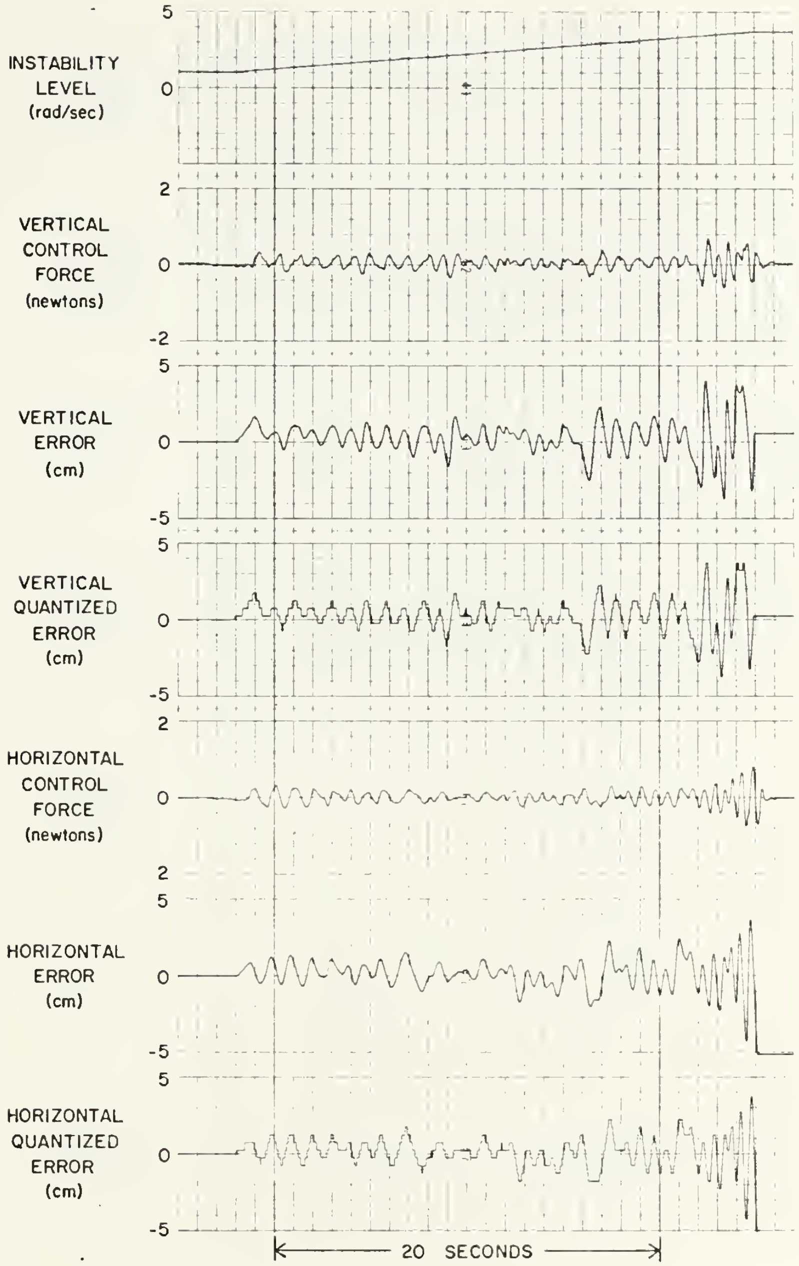
FIGURE 24 TIME HISTORY OF A DUAL-AXIS CRITICAL TASK WITH 0.0635 cm QUANTIZATION INTERVALS



SIGN CONVENTION

Positive vertical control force = Control stick aft
Positive horizontal control force = Control stick right
Positive vertical error = Up on display
Positive horizontal error = Right on display

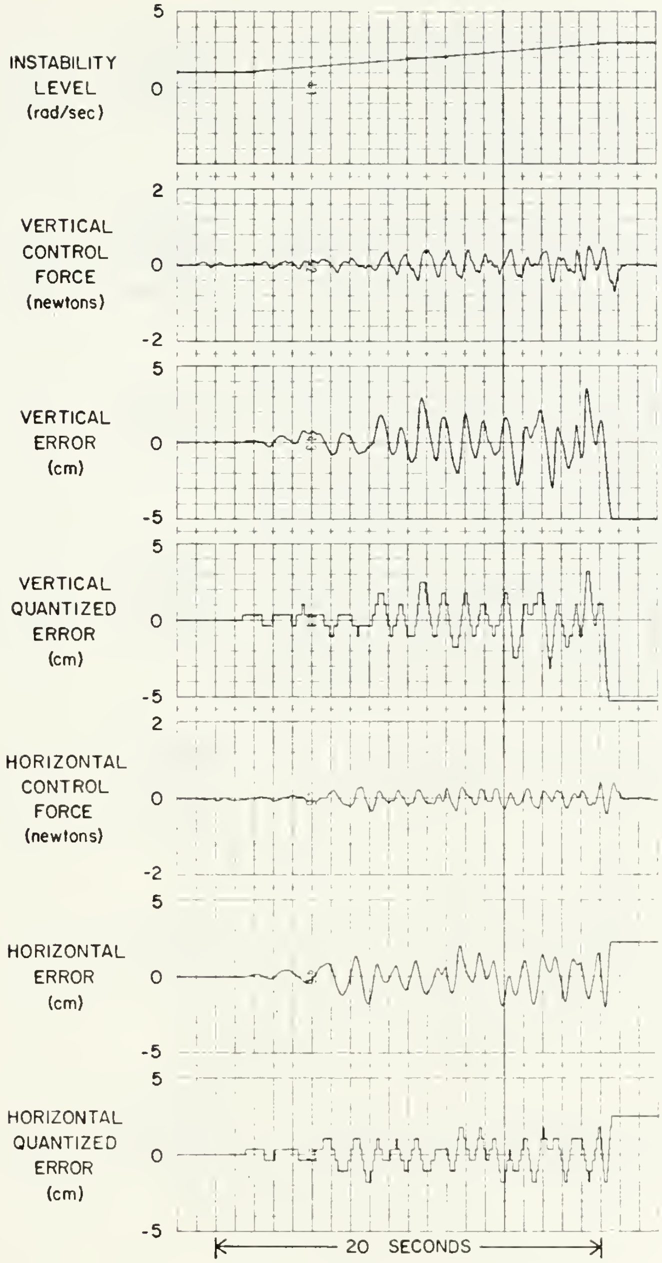
FIGURE 25 TIME HISTORY OF A DUAL-AXIS CRITICAL TASK WITH 0.2540 cm QUANTIZATION INTERVALS



SIGN CONVENTION

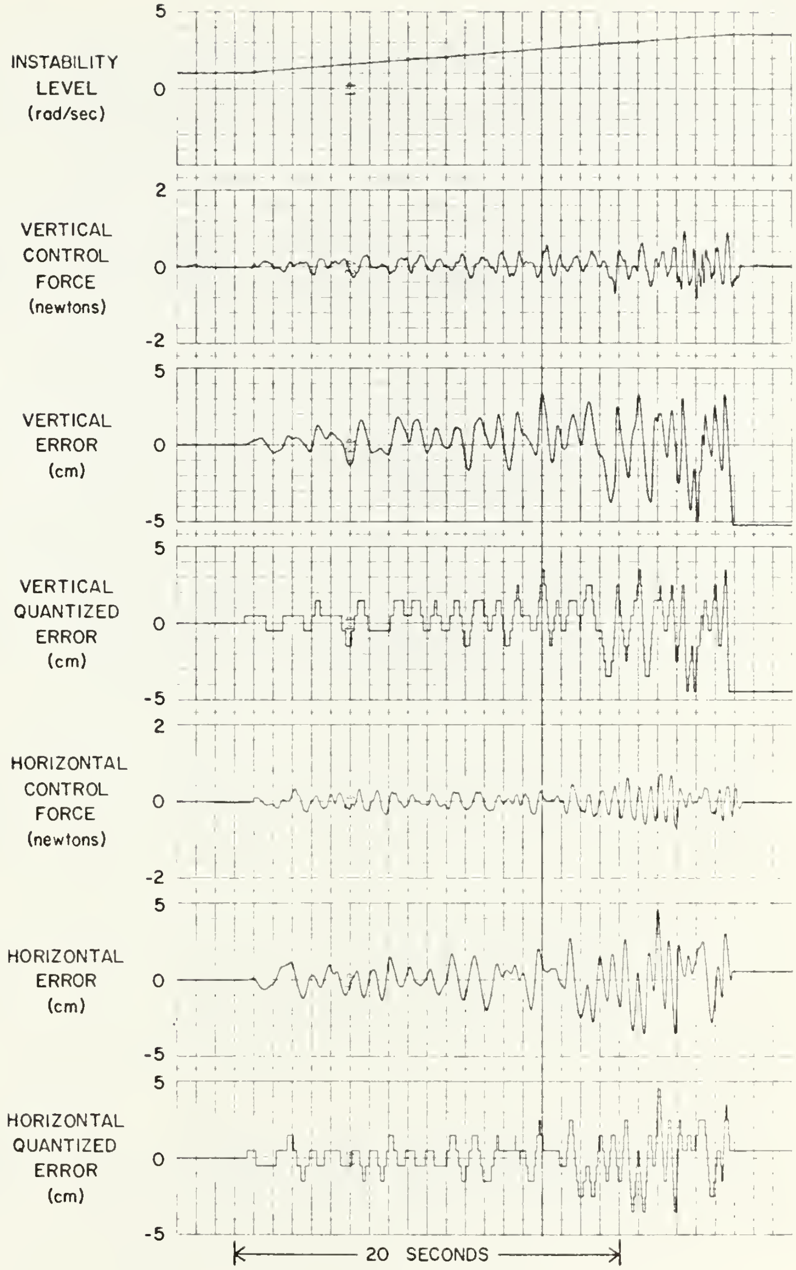
Positive vertical control force = Control stick aft
Positive horizontal control force = Control stick right
Positive vertical error = Up on display
Positive horizontal error = Right on display

FIGURE 26 TIME HISTORY OF A DUAL-AXIS CRITICAL TASK WITH 0.5080 cm QUANTIZATION INTERVALS



SIGN CONVENTION	
	Positive vertical control force = Control stick aft
	Positive horizontal control force = Control stick right
	Positive vertical error = Up on display
	Positive horizontal error = Right on display

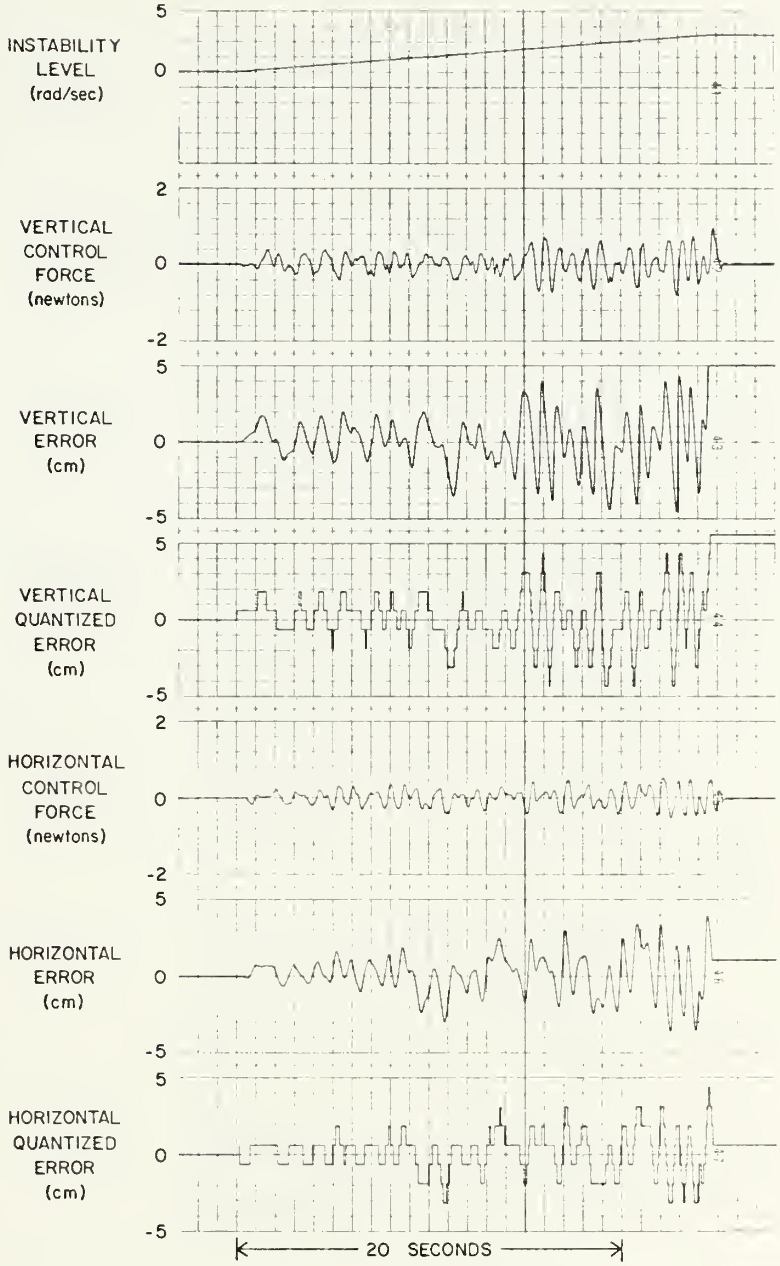
FIGURE 27 TIME HISTORY OF A DUAL-AXIS CRITICAL TASK WITH 0.7257 cm QUANTIZATION INTERVALS



SIGN CONVENTION

Positive vertical control force = Control stick aft
Positive horizontal control force = Control stick right
Positive vertical error = Up on display
Positive horizontal error = Right on display

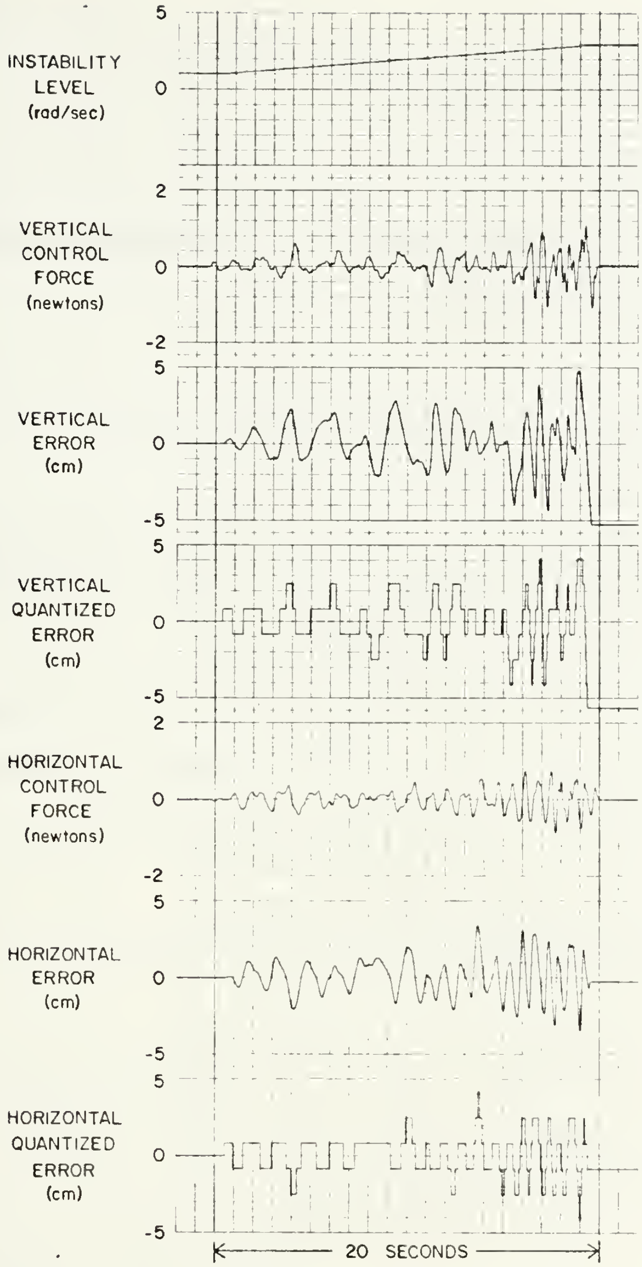
FIGURE 28 TIME HISTORY OF A DUAL-AXIS CRITICAL TASK WITH 1.0160 cm QUANTIZATION INTERVALS



SIGN CONVENTION

Positive vertical control force = Control stick aft
Positive horizontal control force = Control stick right
Positive vertical error = Up on display
Positive horizontal error = Right on display

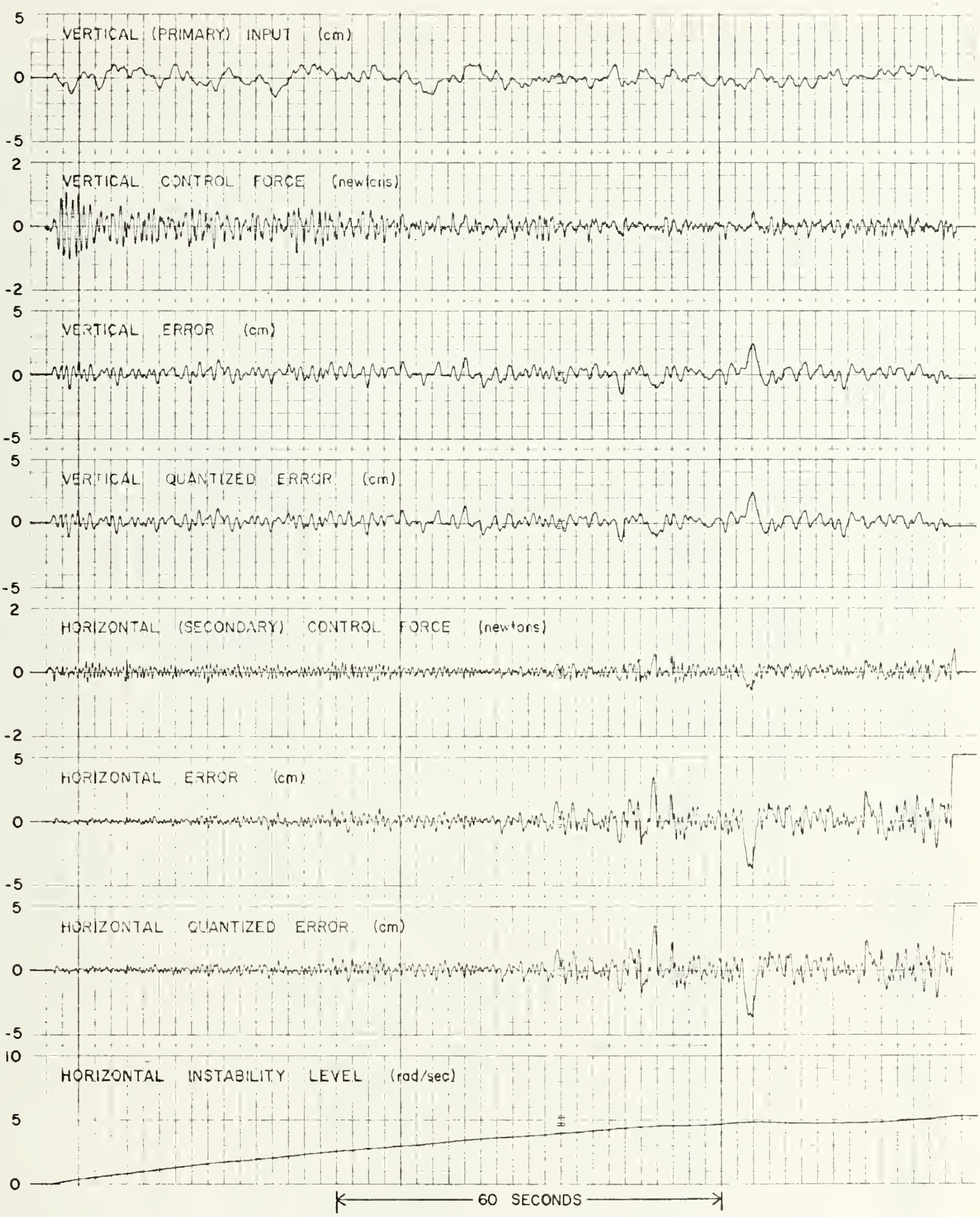
FIGURE 29 TIME HISTORY OF A DUAL-AXIS CRITICAL TASK WITH 1.2700 cm QUANTIZATION INTERVALS



SIGN CONVENTION

Positive vertical control force = Control stick aft
Positive horizontal control force = Control stick right
Positive vertical error = Up on display
Positive horizontal error = Right on display

FIGURE 30 TIME HISTORY OF A DUAL-AXIS CRITICAL TASK WITH 1.6933 cm QUANTIZATION INTERVALS



SIGN CONVENTION	Positive vertical control force = Control stick aft Positive horizontal control force = Control stick right Positive vertical error = Up on display Positive horizontal error = Right on display

FIGURE 31 TIME HISTORY OF A CROSS-ADAPTIVE TASK WITHOUT QUANTIZATION

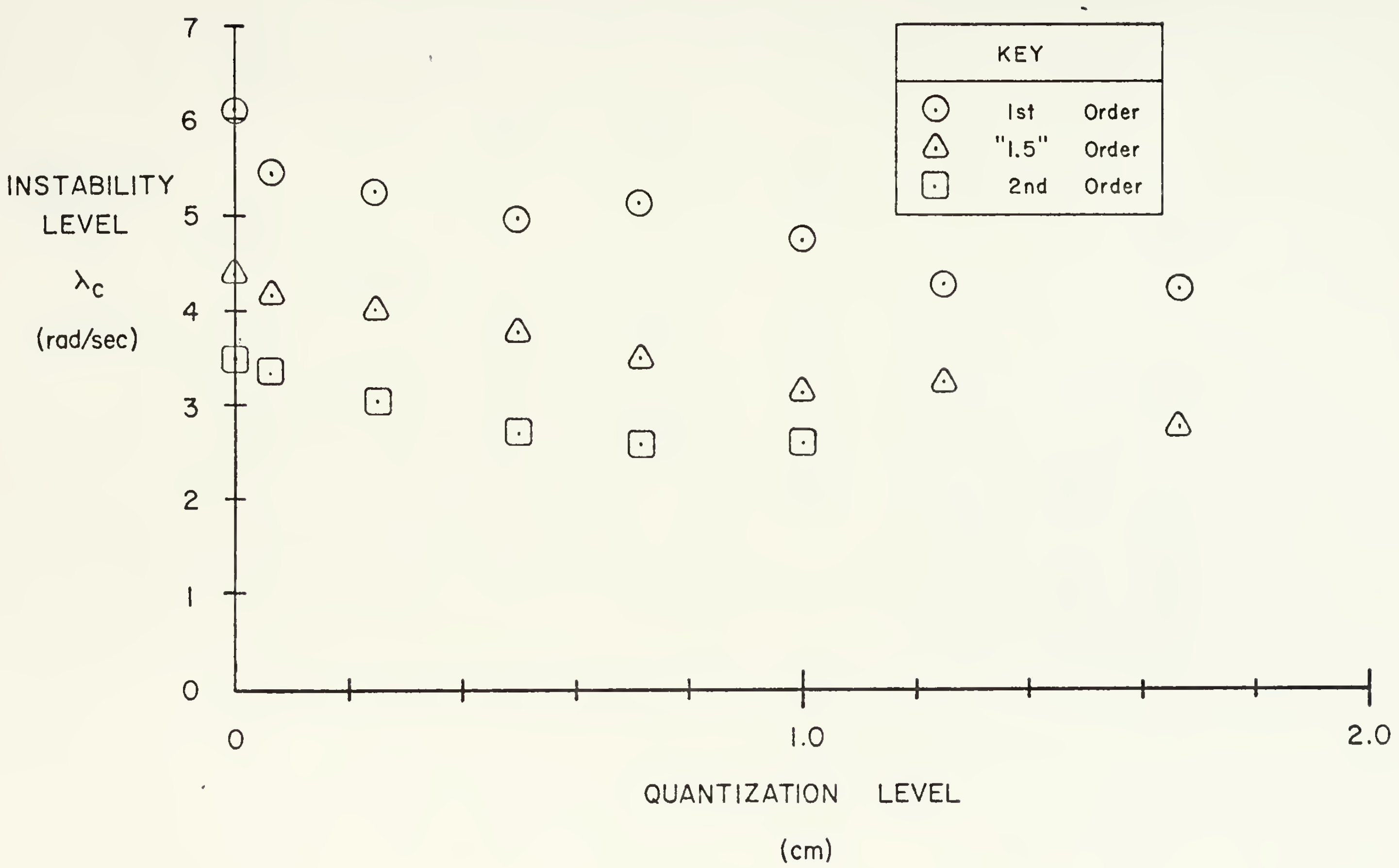


FIGURE 32 SINGLE-AXIS CRITICAL INSTABILITY LEVELS (SUBJECT RH)

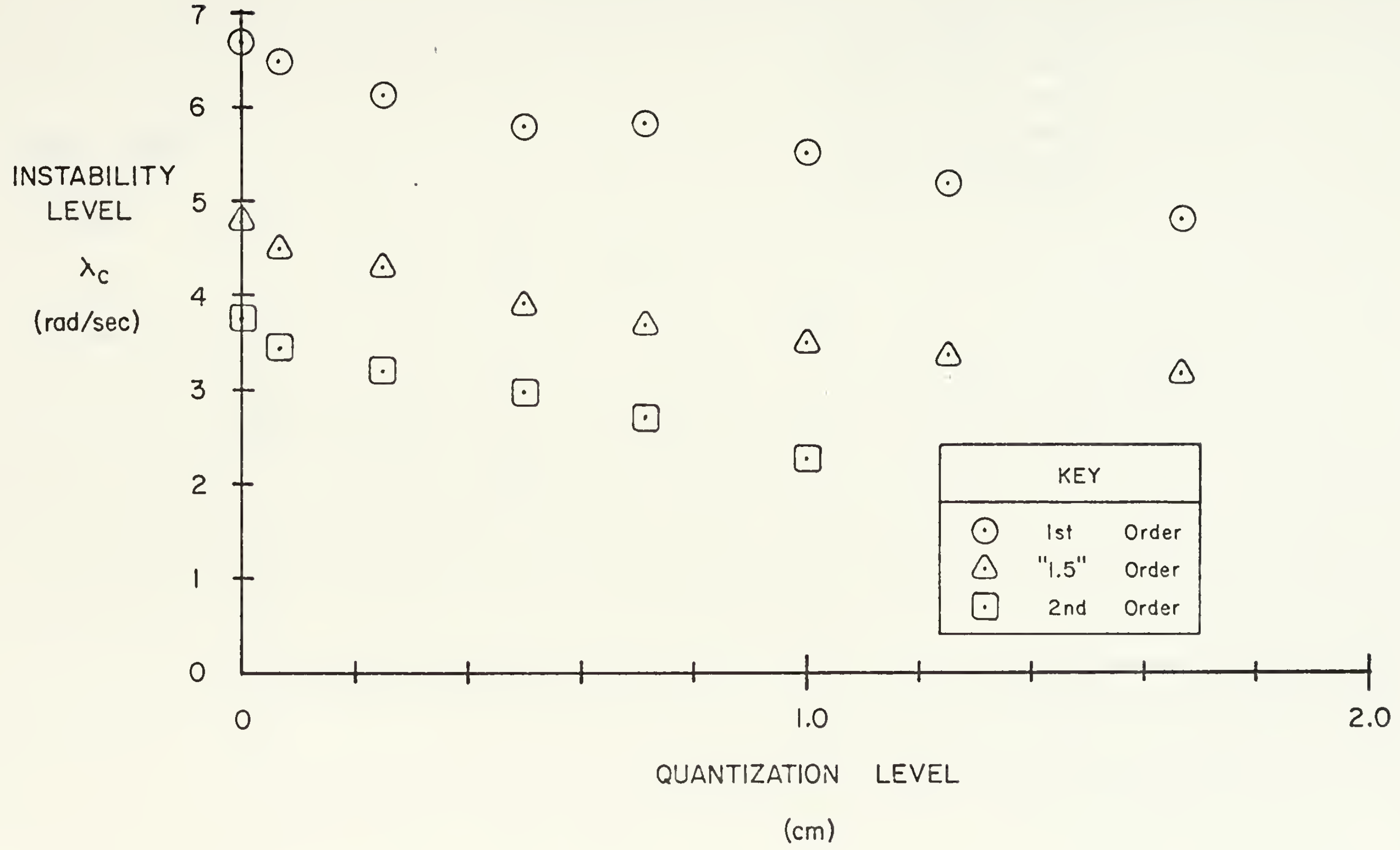


FIGURE 33 SINGLE-AXIS CRITICAL INSTABILITY LEVELS (SUBJECT WT)

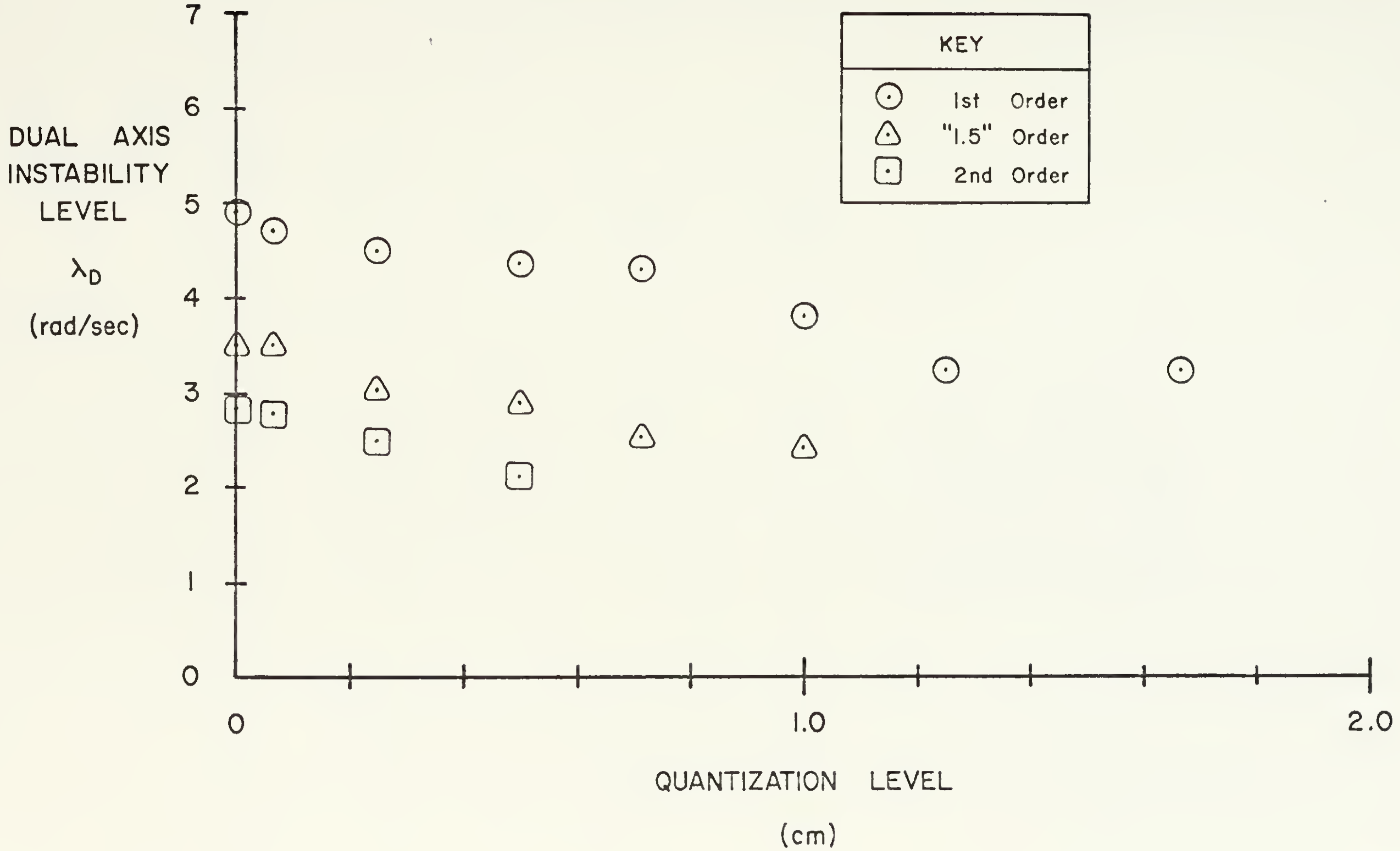


FIGURE 34 DUAL-AXIS CRITICAL INSTABILITY LEVELS (SUBJECT RH)

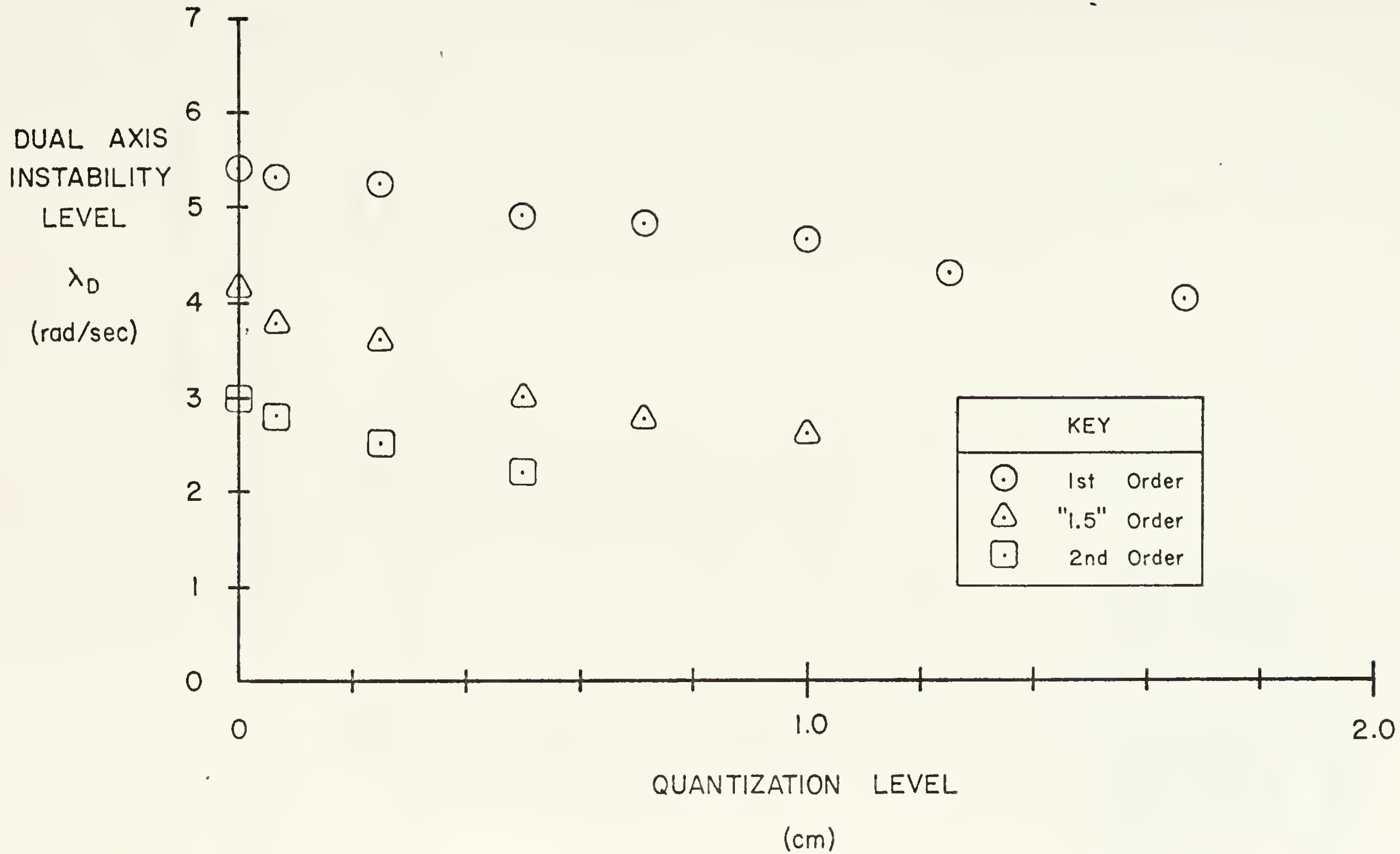


FIGURE 35 DUAL-AXIS CRITICAL INSTABILITY LEVELS. (SUBJECT WT)

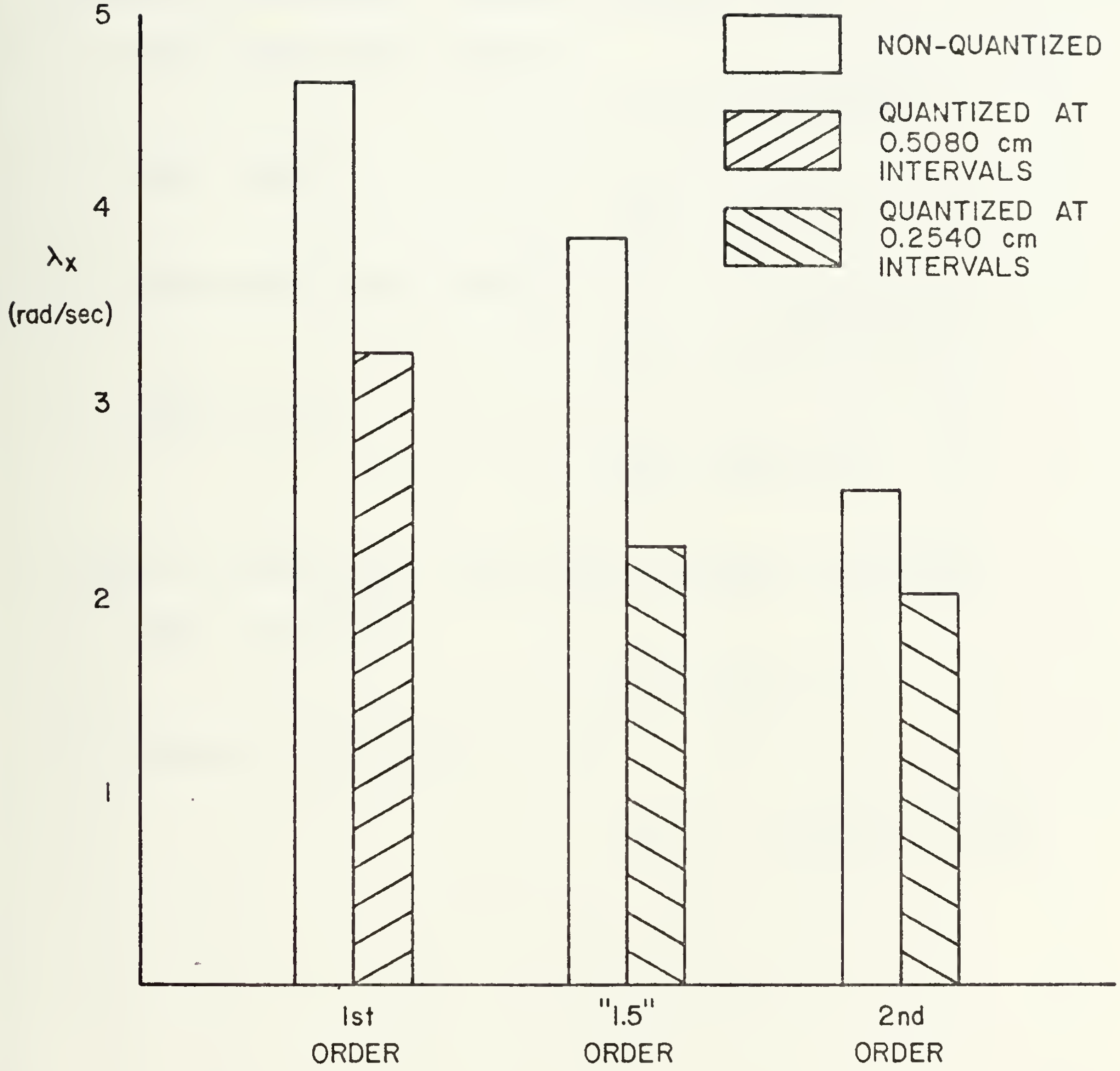


FIGURE 36 CROSS-ADAPTIVE INSTABILITY LEVELS (SUBJECT RH)

APPENDIX C PERFORMANCE MEASURES

1. Online Computations (During Tracking Runs)
   - a. Root-mean-square input:

$$i_{rms} = \sqrt{\frac{1}{T}\int_0^T i^2(t)\,dt}$$

   - b. Mean input:

$$\overline{i(t)} = \frac{1}{T}\int_0^T i(t)\,dt$$

   - c. Root-mean-square error:

$$e_{rms} = \sqrt{\frac{1}{T}\int_0^T e^2(t)\,dt}$$

   - d. Mean error:

$$\overline{e(t)} = \frac{1}{T}\int_0^T e(t)\,dt$$

2. Offline Computations (At End of Series of Runs)
   - a. Mean (Average):

$$\overline{(\ \ )} = \frac{1}{n}\sum_{i=1}^{n}(\ \ )_i$$

   - b. Standard deviation:

$$SD = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}[(\ \ )_i - \overline{(\ \ )}]^2}$$

```
*************************************************************
*                                                           *
*           INSTRUCTIONS FOR USING THIS PROGRAM DECK        *
*                                                           *
*************************************************************


1. PREPARE A DATA CARD WITH THE FOLLOWING DATA:

   A. XNAME1 (A8) = THE FIRST 8 LETTERS OF THE SUBJECT'S NAME
                     (BLANK SPACES ALLOWED)

   B. XNAME2 (A8) = THE SECOND 8 LETTERS OF THE SUBJECT'S NAME
                     (BLANK SPACES ALLOWED)

   C. DATE (A8) = THE CURRENT DATE (BLANK SPACES ALLOWED)

   D. IEXT (I1) = 0 IF SUBJECT HAS HAD NO PRIOR TRACKING
                    EXPERIENCE
                = 1 IF SUBJECT HAS HAD PRIOR TRACKING EXPERIENCE

   E. IEXP (I1) = 0 IF SUBJECT HAS HAD NO AVIATION EXPERIENCE
                = 1 IF SUBJECT IS A PRIVATE PILOT
                = 2 IF SUBJECT IS A MILITARY PILOT

   F. TIME (F5.1) = THE TIME LIMIT DESIRED FOR THE RUNS

   G. LAMBDA (F3.1) = THE INITIAL VALUE OF THE CRITICAL
                       INSTABILITY LEVEL (FOR CRITICAL TASK USE
                       ONLY, BUT MUST BE ENTERED NO MATTER WHAT
                       TASK IS DESIRED)

   H. LAMDOT (F3.1) = THE RATE OF MOVEMENT OF THE CRITICAL
                       INSTABILITY LEVEL (FOR CRITICAL TASK USE
                       ONLY, BUT MUST BE ENTERED NO MATTER WHAT
                       TASK IS DESIRED)

   I. ERRMAX (F4.2) = THE SQUARE OF (0.01 TIMES THE VOLTAGE FROM
                       THE ANALOG COMPUTER WHICH DISPLACES THE
                       DISPLAY PRESENTATION TO THE DISPLAY LIMIT)
                    = 0.25 NORMALLY

   J. CRITE (F3.1) = THE ERROR CRITERION USED IN CROSS-ADAPTIVE
                      TASKS FOR GOVERNING THE RATE OF MOVEMENT OF
                      THE SECONDARY INSTABILITY LEVEL
```

```
*****************************************************************
*                                                               *
*        INSTRUCTIONS FOR USING THIS PROGRAM DECK (CON'T)       *
*                                                               *
*****************************************************************

   THE OVERALL FORMAT OF THIS DATA CARD SHOULD BE:

   3A8,2I1,F5.1,2F3.1,F4.2,F3.1


2. PLACE THE ANALOG COMPUTER IN THE POTSET MODE.

3. PLACE THE ANALOG COMPUTER IN DIGITAL COMPUTER CONTROL.

4. READ THE PROGRAM DECK INTO THE DIGITAL COMPUTER.

5. DURING STEP 4, COMPLETE ALL NECESSARY CONNECTIONS BETWEEN THE
   ANALOG PATCHBOARD AND THE ASSOCIATED EXTERNAL EQUIPMENT.  SET
   P404, P406, P407, P424, P426, AND P427 TO ZERO AND TURN ON ALL
   EXTERNAL EQUIPMENT.

6. WHEN DIGITAL COMPUTER PROGRAM COMPILATION IS COMPLETE, THE
   DIGITAL COMPUTER WILL ASK FOR THE TRACKING TASK TYPE CODE AND
   THE CONTROLLED ELEMENT CODE VIA THE TYPEWRITER.  SUPPLY THE
   DESIRED VALUES VIA THE TYPEWRITER.

7. THE DIGITAL COMPUTER WILL THEN CALL FOR STICK CALIBRATION,
   AGAIN VIA THE TYPEWRITER.  PROCEED AS FOLLOWS:

   A. THE ANALOG COMPUTER WILL BE IN RESET.  WHILE MONITORING Y4
      ON THE ANALOG COMPUTER'S BUILT-IN OSCILLOSCOPE, ADJUST THE
      SIGNAL GENERATOR FEEDING THE CONTROL STICK FOR AN AMPLITUDE
      OF 26 VOLTS (52 VOLTS PEAK-TO-PEAK) ON THE OSCILLOSCOPE AT
      A FREQUENCY OF 400 HZ.

   B. ADJUST THE OTHER SIGNAL GENERATOR FOR A FREQUENCY OF 10 KHZ
      AND AS LARGE AS POSSIBLE AN AMPLITUDE (WITHOUT OVERLOADING
      THE ANALOG COMPUTER).

   C. SET THE VERTICAL LOW-PASS FILTER TO A CUTOFF FREQUENCY OF
      10 HZ.
```

```
*******************************************************************
*                                                                 *
*        INSTRUCTIONS FOR USING THIS PROGRAM DECK (CON'T)         *
*                                                                 *
*******************************************************************


   D. SET THE HORIZONTAL LOW-PASS FILTER TO A CUTOFF FREQUENCY OF
      10 HZ (FOR DUAL-AXIS TRACKING) OR 10 KHZ (FOR SINGLE-AXIS
      TRACKING).

   E. PLACE THE ANALOG COMPUTER IN THE POTSET MODE.  LOCATE THE
      WIRE TO THE INPUT OF P404.  LEAVING ONE END CONNECTED TO
      P404, DISCONNECT THE OTHER END FROM ITS TIE-POINT.  PLACE
      THE FREE END IN A 50-VOLT REFERENCE.

   F. RETURN TO THE RESET MODE.  ADJUST P404 FOR A 2-INCH
      VERTICAL DEFLECTION ON THE DISPLAY.

   G. RETURN TO THE POTSET MODE.  DISCONNECT THE ABOVE-MENTIONED
      WIRE (THE CALIBRATION WIRE) FROM THE 50-VOLT REFERENCE AND
      PLACE IT IN A GROUND POINT.

   H. RETURN TO THE RESET MODE.  ZERO THE DISPLAY WITH THE
      CONTROLS ON THE DISPLAY.  RETURN TO POTSET AND MOVE THE
      CALIBRATION WIRE BACK TO THE 50-VOLT REFERENCE.  REPEAT F.

   I. RETURN TO POTSET.  MOVE THE CALIBRATION WIRE TO THE
      OUTPUT OF A002.

   J. RETURN TO RESET.  WHILE APPLYING A ONE-POUND FORCE (IF A
      FIRST ORDER CONTROLLED ELEMENT IS DESIRED) OR A 0.30-POUND
      FORCE (IF A 1.5 OR SECOND ORDER CONTROLLED ELEMENT IS
      DESIRED) TO THE CONTROL STICK IN THE FORE-AFT DIRECTION,
      ADJUST P406 (CONTROL SENSITIVITY) FOR A 1.75-INCH DISPLAY
      DEFLECTION.  RELEASE THE APPLIED FORCE AND ZERO THE DISPLAY
      WITH P407 (CONTROL BIAS).  RE-APPLY THE FORCE AND RE-ADJUST
      P406.  RELEASE THE FORCE AND RE-ADJUST P407.  CONTINUE THIS
      PROCEDURE UNTIL RELEASING THE FORCE RETURNS THE DISPLAY TO
      ZERO.  THE VERTICAL AXIS IS NOW CALIBRATED.

   K. RETURN TO POTSET.  RETURN THE CALIBRATION WIRE TO ITS
      ORIGINAL TIE-POINT.
```

```
*******************************************************************
*                                                                 *
*       INSTRUCTIONS FOR USING THIS PROGRAM DECK (CON'T)          *
*                                                                 *
*******************************************************************

   L. IF SINGLE-AXIS TRACKING IS USED, THE HORIZONTAL AXIS NEED
      NOT BE CALIBRATED.  ENSURE THAT P424,P426, AND P427 ARE SET
      TO ZERO.  IF DUAL-AXIS TRACKING IS USED, REPEAT STEPS E-K,
      REPLACING P404 WITH P424, P406 WITH P426, P407 WITH P427,
      AND A002 WITH A026.

8. HAVING COMPLETED THE STICK CALIBRATION, SIGNAL READY AS
   INSTRUCTED BY THE TYPEWRITER.

9. THE DIGITAL COMPUTER NOW SETS ALL POTENTIOMETERS ON THE ANALOG
   FOR THE DESIRED TASK.

10. THE TYPEWRITER WILL ASK FOR NQL,KRUN,LRUN.  NQL IS THE NUMBER
    OF INTERVALS INTO WHICH THE POSITIVE HALF OF THE DISPLAY IS TO
    BE DIVIDED FOR QUANTIZATION PURPOSES.  KRUN IS THE NUMBER OF
    THE UPCOMING RUN.  LRUN IS THE NUMBER OF RUNS DESIRED AT THE
    SELECTED QUANTIZATION INTERVAL.  PROVIDE THE DESIRED VALUES
    VIA THE TYPEWRITER.  AFTER A FIVE SECOND DELAY THE FIRST RUN
    WILL START.

11. IF LRUN IS GREATER THAN ONE AND CRITICAL TASKS ARE USED,
    ABOUT A FIFTEEN SECOND DELAY WILL BE EXPERIENCED BETWEEN RUNS.
    IF OTHER THAN CRITICAL TASKS ARE USED, THE TYPEWRITER WILL
    ASK FOR A SIGNAL BEFORE PROCEEDING TO THE NEXT RUN.

12. AFTER THE RUN (IF LRUN IS SET TO ONE) OR AFTER THE SERIES OF
    RUNS (IF LRUN IS GREATER THAN ONE), THE TYPEWRITER WILL ASK
    FOR THE OPTION CODE.  THE OPTIONS AVAILABLE ARE:

    A. MORE RUNS OF THE SAME TRACKING TASK TYPE (EITHER THE SAME
       OR NEW QUANTIZATION INTERVAL).

    B. NEW TRACKING TASK TYPE RUNS (WITH STICK CALIBRATION).

    C. NEW TRACKING TASK TYPE RUNS (WITHOUT STICK CALIBRATION).
```

```
******************************************************************
*                                                                *
*        INSTRUCTIONS FOR USING THIS PROGRAM DECK   (CON'T)      *
*                                                                *
******************************************************************

    D. COMPUTER STOP.

    OPTION A WILL EXECUTE STEPS 11-13.

    OPTION B WILL CAUSE THE TYPEWRITER TO ASK FOR THE TRACKING
    TASK CODE AND THE CONTROLLED ELEMENT CODE.  AFTER THESE HAVE
    BEEN SUPPLIED, STEPS 9-13 WILL BE EXECUTED.

    OPTION C WILL CAUSE THE TYPEWRITER TO ASK FOR THE TRACKING
    TASK CODE AND THE CONTROLLED ELEMENT CODE.  AFTER THESE HAVE
    BEEN SUPPLIED, STEPS 7-13 WILL BE EXECUTED.

    OPTION D WILL TERMINATE THE PROGRAM.
```

```
      ******************************************************************
      *                                                                *
      *                COMPENSATORY TRACKING TASKS                     *
      *                            BY                                  *
      *                 LT. W.M. TEICHGRABER, USN                      *
      *                        FOR USE ON                              *
      *               THE SDS 9300 DIGITAL COMPUTER                    *
      *                   IN CONJUNCTION WITH                          *
      *               THE COMCOR 5000 ANALOG COMPUTER                  *
      *                                                                *
      ******************************************************************

      REAL LAMBDA,LAMDOT,INPUT,INPUT2
      DIMENSION ERR1(50),ERR2(50),XIN(50),XIN2(50),XMI(50),XMI2(50),XPOL
     1E(50),XE1(50),XE2(50)
      COMMON XPOLE2(50),BPOLE(5),NUM(5),ERR(50),SERR(5),NERR(5),XERR1(5)
     1,XERR2(5),XXIN(5),XXIN2(5),XMIN(5),XMIN2(5),XERM1(5),XERM2(5)
      NAMELIST NQL,L,M,K,KRUN,LRUN,LAMBDA,LAMDOT,TIME
      DO 1 J=1,8
      CALL DAC(J,0.0)
    1 CONTINUE
      A=0.1;B=0.01;C=0.9999;D=0.2;F=0.03;G=0.0005;H=0.1170;R=0.7872;S=0.
     11340;X=0.5;W=0.2340
      CALL POTSET
      CALL SETPOT(4HP017,X,4HP021,R,4HP022,R,4HP027,S,4HP043,A,4HP042,A,
     14HP012,D,4HP013,D,4HP045,D,4HP047,D,4HP015,X,4HP032,A,4HP033,A,4HP
     1035,D,4HP034,D,4HP007,G)

      ******************************************************************
      *                                                                *
      *                      INPUT VARIABLES                           *
      *                                                                *
      ******************************************************************

      READ(5,2) XNAME1,XNAME2,DATE,IEXT,IEXP,TIME,LAMBDA,LAMDOT,ERRMAX,C
     1RITE
    2 FORMAT(3A8,2I1,F5.1,2F3.1,F4.2,F3.1)
      OUTPUT(102) 'PLEASE GIVE ME:'
      OUTPUT(102) '    M=1 FOR SINGLE-AXIS CRITICAL TRACKING'
      OUTPUT(102) '     =2 FOR DUAL-AXIS CRITICAL'
      OUTPUT(102) '     =3 FOR SINGLE-AXIS SUBCRITICAL'
      OUTPUT(102) '     =4 FOR DUAL-AXIS SUBCRITICAL'
      OUTPUT(102) '     =5 FOR CROSS-ADAPTIVE'
      OUTPUT(102) '     =6 FOR CROSS-ADAPTIVE TRAINING'
      OUTPUT(102) '    K=0 FOR FIRST ORDER CONTROLLED ELEMENT'
      OUTPUT(102) '     =1 FOR 1.5 ORDER'
      OUTPUT(102) '     =2 FOR SECOND ORDER'
      INPUT(101)
```

```
 *******************************************************************
 *                                                                 *
 *                       STICK CALIBRATION                         *
 *                                                                 *
 *******************************************************************

3 CALL SETPOT(4HP050,C,4HP005,0,4HP006,0,4HP024,0,4HP003,0,4HP054,C,
 14HP057,0,4HP030,0,4HP055,0,4HP056,C);CALL RESET(10)
  OUTPUT(102) 'CALIBRATE STICK.  SIGNAL COMPLETE WITH * AND A C/R.'
  INPUT(101)

 *******************************************************************
 *                                                                 *
 *                         POTSET ROUTINE                          *
 *                                                                 *
 *******************************************************************

4 CALL POTSET;IF(M.GT.1) GO TO 7
  IF(K.GT.0) GO TO 5
  CALL SETPOT(4HP010,0,4HP006,0,4HP005,0,4HP003,0,4HP051,0,4HP050,C,
 14HP001,B,4HP000,A,4HP041,0,4HP025,0,4HP054,0,4HP053,0,4HP030,0,4HP
 1024,0,4HP057,0,4HP040,0,4HP055,C,4HP056,0)
  GO TO 19
5 IF(K.GT.1) GO TO 6
  CALL SETPOT(4HP010,0,4HP006,0,4HP005,0,4HP003,C,4HP051,D,4HP050,0,
 14HP001,B,4HP000,A,4HP041,0,4HP025,0,4HP054,0,4HP053,0,4HP030,0,4HP
 1024,0,4HP057,0,4HP040,0,4HP055,C,4HP056,0)
  GO TO 19
6 CALL SETPOT(4HP010,0,4HP006,0,4HP005,0,4HP003,C,4HP051,0,4HP050,0,
 14HP001,B,4HP000,A,4HP041,0,4HP025,0,4HP054,0,4HP053,0,4HP030,0,4HP
 1024,0,4HP057,0,4HP040,0,4HPOKK,C,4HP056,0)
  GO TO 19
7 IF(M.GT.2) GO TO 10
  IF(K.GT.0) GO TO 8
  CALL SETPOT(4HP010,0,4HP006,0,4HP005,0,4HP003,0,4HP051,0,4HP050,C,
 14HP001,B,4HP000,A,4HP041,A,4HP025,B,4HP054,C,4HP053,0,4HP030,0,4HP
 1024,0,4HP057,0,4HP040,0,4HP055,0,4HP056,C)
  GO TO 19
8 IF(K.GT.1) GO TO 9
  CALL SETPOT(4HP010,0,4HP006,0,4HP005,0,4HP003,C,4HP051,D,4HP050,0,
 14HP001,B,4HP000,A,4HP041,A,4HP025,B,4HP054,0,4HP053,D,4HP030,C,4HP
 1024,0,4HP057,0,4HP040,0,4HP055,0,4HP056,C)
  GO TO 19
9 CALL SETPOT(4HP010,0,4HP006,0,4HP005,0,4HP003,C,4HP051,0,4HP050,0,
 14HP001,B,4HP000,A,4HP041,A,4HP025,B,4HP054,0,4HP053,0,4HP030,C,4HP
 1024,0,4HP057,0,4HP040,0,4HP055,0,4HP056,C)
  GO TO 19
10 IF(M.GT.3) GO TO 13
```

```
*******************************************************************
*                                                                 *
*                     POTSET ROUTINE (CON'T)                      *
*                                                                 *
*******************************************************************

      IF(K.GT.0) GO TO 11
      CALL SETPOT(4HP010,W,4HP006,C,4HP005,0,4HP003,0,4HP051,0,4HP050,0,
     14HP001,0,4HP000,0,4HP041,0,4HP025,0,4HP054,0,4HP053,0,4HP030,0,4HP
     1024,0,4HP057,0,4HP040,0,4HP055,C,4HP056,0)
      GO TO 19
   11 IF(K.GT.1) GO TO 12
      CALL SETPOT(4HP010,H,4HP006,0,4HP005,C,4HP003,0,4HP051,D,4HP050,0,
     14HP001,0,4HP000,0,4HP041,0,4HP025,0,4HP054,0,4HP053,0,4HP030,0,4HP
     1024,0,4HP057,0,4HP040,0,4HP055,C,4HP056,0)
      GO TO 19
   12 CALL SETPOT(4HP010,H,4HP006,0,4HP005,C,4HP003,0,4HP051,0,4HP050,0,
     14HP001,0,4HP000,0,4HP041,0,4HP025,0,4HP054,0,4HP053,0,4HP030,0,4HP
     1024,0,4HP057,0,4HP040,0,4HP055,C,4HP056,0)
      GO TO 19
   13 IF(M.GT.4) GO TO 16
      IF(K.GT.0) GO TO 14
      CALL SETPOT(4HP010,W,4HP006,C,4HP005,0,4HP003,0,4HP051,0,4HP050,0,
     14HP001,0,4HP000,0,4HP041,0,4HP025,0,4HP054,0,4HP053,0,4HP030,0,4HP
     1024,C,4HP057,0,4HP040,W,4HP055,0,4HP056,C)
      GO TO 19
   14 IF(K.GT.1) GO TO 15
      CALL SETPOT(4HP010,H,4HP006,0,4HP005,C,4HP003,0,4HP051,D,4HP050,0,
     14HP001,0,4HP000,0,4HP041,0,4HP025,0,4HP054,0,4HP053,D,4HP030,0,4HP
     1024,0,4HP057,C,4HP040,H,4HP055,0,4HP056,C)
      GO TO 19
   15 CALL SETPOT(4HP010,H,4HP006,0,4HP005,C,4HP003,0,4HP051,0,4HP050,0,
     14HP001,0,4HP000,0,4HP041,0,4HP025,0,4HP054,0,4HP053,0,4HP030,0,4HP
     1024,0,4HP057,C,4HP040,H,4HP055,0,4HP056,C)
      GO TO 19
   16 IF(K.GT.0) GO TO 17
      CALL SETPOT(4HP010,W,4HP006,C,4HP005,0,4HP003,0,4HP051,0,4HP050,0,
     14HP001,0,4HP000,0,4HP041,A,4HP025,F,4HP054,C,4HP053,0,4HP030,0,4HP
     1024,0,4HP040,0,4HP055,0,4HP056,C)
      GO TO 19
   17 IF(K.GT.1) GO TO 18
      CALL SETPOT(4HP010,H,4HP006,0,4HP005,C,4HP003,0,4HP051,D,4HP050,0,
     14HP001,0,4HP000,0,4HP041,A,4HP025,F,4HP054,C,4HP053,0,4HP030,0,4HP
     1024,0,4HP057,0,4HP040,0,4HP055,0,4HP056,C)
      GO TO 19
   18 CALL SETPOT(4HP010,H,4HP006,0,4HP005,C,4HP003,0,4HP051,0,4HP050,0,
     14HP001,0,4HP000,0,4HP041,A,4HP025,F,4HP054,C,4HP053,0,4HP030,0,4HP
     1024,0,4HP057,0,4HP040,0,4HP055,0,4HP056,C)
```

```
   ********************************************************************
   *                                                                  *
   *              INPUT RUN VARIABLES + DELAY 5 SECONDS               *
   *                                                                  *
   ********************************************************************

19 CALL RESET(10)
20 OUTPUT(102) 'PLEASE GIVE ME:  NQL,KRUN,LRUN'
   INPUT(101)
21 CALL WRITECLOCK(0);CALL STARTCLOCK
22 CALL READCLOCK(Y)
   IF(Y.LT.300) GO TO 22
   CALL STOPCLOCK

   ********************************************************************
   *                                                                  *
   *                 INITIALIZE VARIABLES + START RUN                 *
   *                                                                  *
   ********************************************************************

   QL=0.5/NQL
   E=0.0;E2=E;RMSE1=E;RMSE2=E;RMSI1=E;RMSI2=E;RMSE=E;T1=E;AI=0.01
   I2=1;J2=0;FPOLE=E;TIM2=TIME-20.0;INC=0;CALL DAC(6,9999)
   IF(M.GT.4) CALL DAC(6,0.0)
   CALL COMPUTE;CALL WRITECLOCK(0);CALL STARTCLOCK
23 CALL READCLOCK(V)
   AV=V/60.0;IF(AV.LT.AI) GO TO 23

   ********************************************************************
   *                                                                  *
   *          QUANTIZATION + ON-LINE DATA REDUCTION ROUTINES          *
   *                                                                  *
   ********************************************************************

   CALL QUANT(E,QL,QE,1,1)
   IF(M.EQ.2.OR.M.EQ.4) CALL QUANT(E2,QL,QE2,4,4)
   IF(M.GT.4) CALL ADK(4,E2)
   IF(M.LT.3) GO TO 24
   CALL ERROR(T1,AV,RMSE1,E,1)
   CALL ERROR(T1,AV,RMSI1,INPUT,3)
   CALL ERMEAN(T1,AV,XI,INPUT,3)
   CALL ERMEAN(T1,AV,ERM1,E,1)
   IF(M.LT.4.OR.M.GT.4) GO TO 24
   CALL ERROR(T1,AV,RMSE2,E2,4)
   CALL ERROR(T1,AV,RMSI2,INPUT2,23)
   CALL ERMEAN(T1,AV,XI2,INPUT2,23)
   CALL ERMEAN(T1,AV,ERM2,E2,4)
24 T1=AV
```

```
      *****************************************************************
      *                                                               *
      *           CROSS-ADAPTIVE SECONDARY INSTABILITY CONTROL        *
      *                                                               *
      *****************************************************************

      IF(M.LT.5.OR.M.GT.5) GO TO 26
      IF(INC.GT.0) GO TO 25
      CALL ADK(7,EFL)
      EFL=ABS(EFL)
      CALL DAC(2,EFL)
      CALL ADK(20,EF10)
      CALL ADK(21,EF5)
      ERCRIT=(ABS(EF10-EF5))*(2.54/0.25)
      ERRIN=SQRT(RMSI1)/100.0
      IF(ERCRIT.GT.ERRIN) GO TO 26
      INC=INC+1
      RMSERR=CRITE*SQRT(RMSE1)
   25 CALL DAC(6,0.3)
      CALL ADK(1,ER3);ER3=ABS(ER3*2.54/0.25);PP=(RMSERR-ER3)*1.3333
      IF(PP.GT.0.50) PP=0.50
      IF(PP.LT.-0.999) PP=-0.9999
      CALL ADK(6,POLE2)
      IF(POLE2.LT.0.10) PP=0.50
      CALL DAC(6,PP)
      J2=0
      IF(AV.LT.TIM2) GO TO 26
      J2=1
      CALL ADK(0,FP)
      FPOLE=FPOLE+10.0*FP
      TIM2=TIM2+1.0

      *****************************************************************
      *                                                               *
      *            STOP IF DISPLAY OR TIME LIMITS EXCEEDED            *
      *                                                               *
      *****************************************************************

   26 CALL ADK(2,POLE)
      I2=I2+J2
      EA=E**2
      EA2=E2**2
      AI=AI+0.0100
      IF(AV.GT.TIME.OR.EA.GT.ERRMAX.OR.EA2.GT.ERRMAX) GO TO 27
      GO TO 23
   27 CALL STOPCLOCK;CALL HOLD
```

```
      ****************************************************************
      *                                                              *
      *                     OUTPUT ON-LINE DATA                      *
      *                                                              *
      ****************************************************************

      IF(M.LT.3) XPOLE(KRUN)=10.0*POLE
      IF(M.LT.3) CPOLE=XPOLE(KRUN)
      IF(M.EQ.5.AND.I2.GT.1) FPOLE=FPOLE/(I2-1)
      IF(M.EQ.5) XPOLE(KRUN)=FPOLE
      IF(KRUN.EQ.1) OUTPUT(102) NQL
      OUTPUT(102) KRUN
      IF(M.LT.3) OUTPUT(102) CPOLE
      IF(M.LT.3) GO TO 28
      RMSE1=SQRT(RMSE1);RMSI1=SQRT(RMSI1)
      RMSE2=SQRT(RMSE2);RMSI2=SQRT(RMSI2)
      XIN(KRUN)=RMSI1;XIN2(KRUN)=RMSI2;ERR1(KRUN)=RMSE1;ERR2(KRUN)=RMSE2
      XMI(KRUN)=XI;XMI2(KRUN)=XI2;XE1(KRUN)=ERM1;XE2(KRUN)=ERM2
      OUTPUT(102) XI,RMSI1,ERM1,RMSE1
      IF(M.EQ.4) OUTPUT(102) XI2,RMSI2,ERM2,RMSE2
      IF(M.GT.4) OUTPUT(102) RMSERR
      IF(M.EQ.5) OUTPUT(102) FPOLE
   28 DO 29 J=1,8
      CALL DAC(J,0.0)
   29 CONTINUE
      CALL RESET(10)
      CALL WRITE(M,XNAME1,XNAME2,DATE,IEXT,IEXP,LAMBDA,LAMDOT,NQL,KRUN,X
     1POLE(KRUN),XIN(KRUN),XIN2(KRUN),ERR1(KRUN),ERR2(KRUN),XMI(KRUN),XM
     1I2(KRUN),RMSERR,K,XE1(KRUN),XE2(KRUN))

      ****************************************************************
      *                                                              *
      *                   NEW RUN OR STOP DECISION                   *
      *                                                              *
      ****************************************************************

      IF(M.GT.2) GO TO 30
      IF(POLE.LT.0.12) GO TO 53
   30 KRUN=KRUN+1
      IF(KRUN.GT.LRUN) GO TO 31
      IF(M.LT.3) GO TO 21
      OUTPUT(102) 'SIGNAL READY FOR NEXT RUN WITH A * AND A C/R.'
      INPUT(101)
      GO TO 21
   31 IF(LRUN.LT.5) GO TO 53
```

```
*******************************************************************
*                                                                 *
*              CRITICAL TASK OFF-LINE DATA REDUCTION              *
*                                                                 *
*******************************************************************

   IF(M.EQ.3.OR.M.EQ.4) GO TO 37
   DO 32 J=1,LRUN
   XPOLE2(J)=XPOLE(J)
32 CONTINUE
   CALL BIG(XPOLE2,LRUN,BPOLE,NUM);CALL AVRAGE(BPOLE,APOLE,SPOLE)
   WRITE(6,33) LRUN
33 FORMAT(//' ','THE FIVE BEST OF THE PREVIOUS ',I2,' RUNS ARE:'//)
   DO 35 I=1,5
   WRITE(6,34) NUM(I),BPOLE(I)
34 FORMAT(' ',10X,'RUN NO. = ',I2,10X,'LAMBDA = ',F7.5,' RAD/SEC')
35 CONTINUE
   WRITE(6,36) APOLE,SPOLE
36 FORMAT(//' ','THE MEAN VALUE OF THE CRITICAL INSTABILITY LEVEL'/'
  1',6X,'FOR THESE 5 RUNS WAS ',F8.5,' RAD/SEC.'/' ','THE STANDARD DE
  1VIATION WAS ',F8.5,' RAD/SEC.')
   GO TO 53

*******************************************************************
*                                                                 *
*            SUBCRITICAL TASK OFF-LINE DATA REDUCTION             *
*                                                                 *
*******************************************************************

37 IF(M.LT.4.OR.M.GT.4) GO TO 39
   DO 38 I=1,LRUN
   ERR(I)=SQRT(ERR1(I)**2+ERR2(I)**2)
38 CONTINUE
   GO TO 41
39 DO 40 I=1,LRUN
   ERR(I)=ERR1(I)
40 CONTINUE
41 CALL SMALL(ERR,LRUN,NERR)
   DO 42 J=1,5
   LQ=NERR(J);XERR1(J)=ERR1(LQ);XXIN(J)=XIN(LQ);XMIN(J)=XMI(LQ)
   XERM1(J)=XE1(LQ)
   IF(M.LT.4.OR.M.GT.4) GO TO 42
   XERR2(J)=ERR2(LQ);XXIN2(J)=XIN2(LQ);XMIN2(J)=XMI2(LQ)
   XERM2(J)=XE2(LQ)
42 CONTINUE
   WRITE(6,43) LRUN
43 FORMAT(//' ','THE FIVE BEST OF THE PREVIOUS ',I2,' RUNS ARE:'//)
   WRITE(6,44)
```

```
*************************************************************************
*                                                                       *
*         SUBCRITICAL TASK OFF-LINE DATA REDUCTION (CON'T)              *
*                                                                       *
*************************************************************************

44    FORMAT(' ',10X,'VERTICAL',6X,'VERTICAL',6X,'VERTICAL',6X,'VERTICAL
     1'/' ',' RUN',8X,'MEAN',10X,'RMS',11X,'MEAN',10X,'RMS'/' ','NUMBER'
     1,5X,'INPUT',9X,'INPUT',9X,'ERROR',9X,'ERROR'/' ',11X,'(CM.)',9X,'(
     1CM.)',9X,'(CM.)',9X,'(CM.)'//)
      DO 46 I=1,5
      LQ=NERR(I);WRITE(6,45) LQ,XMI(LQ),XIN(LQ),XE1(LQ),ERR1(LQ)
45    FORMAT(' ',2X,I2,4F14.7)
46    CONTINUE
      IF(M.EQ.4) WRITE(6,47)
47    FORMAT(//' ',9X,'HORIZONTAL',4X,'HORIZONTAL',4X,'HORIZONTAL',4X,'H
     1ORIZONTAL'/' ',' RUN',8X,'MEAN',10X,'RMS',11X,'MEAN',10X,'RMS'/' '
     1,'NUMBER',5X,'INPUT',9X,'INPUT',9X,'ERROR',9X,'ERROR'/' ',11X,'(CM
     1.)',9X,'(CM.)',9X,'(CM.)',9X,'(CM.)'//)
      IF(M.LT.4.OR.M.GT.4) GO TO 49
      DO 49 I=1,5
      LQ=NERR(I);WRITE(6,48) LQ,XMI2(LQ),XIN2(LQ),XE2(LQ),ERR2(LQ)
48    FORMAT(' ',2X,I2,4F14.7)
49    CONTINUE
      CALL AVRAGE(XERR1,AERR1,SERR1);CALL AVRAGE(XXIN,AXIN,SXIN)
      CALL AVRAGE(XMIN,AMIN,SMIN);CALL AVRAGE(XERM1,AERM1,SERM1)
      IF(M.LT.4.OR.M.GT.4) GO TO 50
      CALL AVRAGE(XERR2,AERR2,SERR2);CALL AVRAGE(XXIN2,AXIN2,SXIN2)
      CALL AVRAGE(XMIN2,AMIN2,SMIN2);CALL AVRAGE(XERM2,AERM2,SERM2)
50    WRITE(6,51) AMIN,SMIN,AXIN,SXIN,AERM1,SERM1,AERR1,SERR1
51    FORMAT(//' ',2X,'THE MEAN VALUE OF THE VERTICAL MEAN INPUT WAS ',F
     19.7,' CM.'/' ',21X,'THE STANDARD DEVIATION WAS ',F9.7,' CM.'//' ',
     13X,'THE MEAN VALUE OF THE VERTICAL RMS INPUT WAS ',F9.7,' CM.'/' '
     1,21X,'THE STANDARD DEVIATION WAS ',F9.7,' CM.'//' ',2X,'THE MEAN V
     1ALUE OF THE VERTICAL MEAN ERROR WAS ',F9.7,' CM.'/' ',21X,'THE STA
     1NDARD DEVIATION WAS ',F9.7,' CM.'//' ',3X,'THE MEAN VALUE OF THE V
     1ERTICAL RMS ERROR WAS ',F9.7,' CM.'/' ',21X,'THE STANDARD DEVIATIO
     1N WAS ',F9.7,' CM.')
      IF(M.EQ.4) WRITE(6,52) AMIN2,SMIN2,AXIN2,SXIN2,AERM2,SERM2,AERR2,S
     1ERR2
52    FORMAT(/'1','THE MEAN VALUE OF THE HORIZONTAL MEAN INPUT WAS ',F9.
     17,' CM.'/' ',21X,'THE STANDARD DEVIATION WAS ',F9.7,' CM.'//' ','
     1THE MEAN VALUE OF THE HORIZONTAL RMS INPUT WAS ',F9.7,' CM.'/' ',2
     11X,'THE STANDARD DEVIATION WAS ',F9.7,' CM.'//' ','THE MEAN VALUE 
     1OF THE HORIZONTAL MEAN ERROR WAS ',F9.7,' CM.'/' ',21X,'THE STANDA
     1RD DEVIATION WAS ',F9.7,' CM.'//' ',' THE MEAN VALUE OF THE HORIZO
     1NTAL RMS ERROR WAS ',F9.7,' CM.'/' ',21X,'THE STANDARD DEVIATION W
     1AS ',F9.7,' CM.')
```

```
   *****************************************************************
   *                                                               *
   *        LIST OPTIONS FOR NEW RUNS, NEW RUN TYPE, OR STOP       *
   *                                                               *
   *****************************************************************

53 CALL DAC(1,0.6)
   OUTPUT(102) 'L=0 FOR NEW NQL OR LRUN; L=1 FOR NEW RUN TYPE AND STI
  1CK CALIBRATION:'
   OUTPUT(102) 'L=2 FOR NEW RUN TYPE WITHOUT STICK CALIBRATION; L=3 T
  1O STOP.'
   CALL DAC(1,0.0)
   INPUT(101)
   IF(L.GT.0) GO TO 54
   GO TO 20
54 IF(L.GT.2) GO TO 55
   OUTPUT(102) 'PLEASE GIVE ME M AND K'
   INPUT(101)
   IF(L.EQ.1) GO TO 3
   IF(L.EQ.2) GO TO 4
55 STOP
   END
```

```
******************************************************************
*                                                                *
*                    QUANTIZATION SUBROUTINE                     *
*                                                                *
******************************************************************


SUBROUTINE QUANT(AA,BB,CC,II,JJ)
CALL ADK(II,AA)
J=AA/BB
CC=J*BB+SIGN(BB/2.0,AA)
CALL DAC(JJ,CC)
RETURN
END
```

```
******************************************************************
*                                                                *
*                RMS ERROR + RMS INPUT SUBROUTINE                *
*                                                                *
******************************************************************


SUBROUTINE ERROR(BB,CC,DD,EE,II)
CALL ADK(II,EE)
GG=(2.54/0.25)*EE
DD=((GG**2)*(CC-BB)+DD*BB)/CC
RETURN
END
```

```
******************************************************************
*                                                                *
*               MEAN ERROR + MEAN INPUT SUBROUTINE               *
*                                                                *
******************************************************************


SUBROUTINE ERMEAN(AA,BB,CC,DD,JJ)
CALL ADK(JJ,DD)
GG=(2.54/0.25)*DD
CC=(GG*(BB-AA)+CC*AA)/BB
RETURN
END
```

```
      *******************************************************************
      *                                                                 *
      *                        WRITE SUBROUTINE                         *
      *                                                                 *
      *******************************************************************

      SUBROUTINE WRITE(MM,X1,X2,DD,IT,IP,XA,XD,NN,KK,X,XI1,XI2,EE1,EE2,E
     1M1,EM2,RR,KK2,XX1,XX2)
      IF(MM.GT.1) GO TO 402
      WRITE(6,401)
  401 FORMAT('1','THIS WAS A SINGLE-AXIS CRITICAL TASK.')
      GO TO 410
  402 IF(MM.GT.2) GO TO 404
      WRITE(6,403)
  403 FORMAT('1','THIS WAS A DUAL-AXIS CRITICAL TASK.')
      GO TO 410
  404 IF(MM.GT.3) GO TO 406
      WRITE(6,405)
  405 FORMAT('1','THIS WAS A SINGLE-AXIS SUBCRITICAL TASK.')
      GO TO 410
  406 IF(MM.GT.4) GO TO 408
      WRITE(6,407)
  407 FORMAT('1','THIS WAS A DUAL-AXIS SUBCRITICAL TASK.')
      GO TO 410
  408 WRITE(6,409)
  409 FORMAT('1','THIS WAS A CROSS-ADAPTIVE TASK.')
  410 IF(KK2.GT.0) GO TO 412
      WRITE(6,411)
  411 FORMAT(' ','A FIRST ORDER CONTROLLED ELEMENT WAS USED.')
      GO TO 416
  412 IF(KK2.GT.1) GO TO 414
      WRITE(6,413)
  413 FORMAT(' ','A 1.5 ORDER CONTROLLED ELEMENT WAS USED.')
      GO TO 416
  414 WRITE(6,415)
  415 FORMAT(' ','A SECOND ORDER CONTROLLED ELEMENT WAS USED.')
  416 WRITE(6,417) X1,X2
  417 FORMAT(' ','THE SUBJECT WAS ',2A8,'.')
      WRITE(6,418) DD
  418 FORMAT(' ','THE DATE WAS ',A8,'.')
      IF(IT.GT.0) GO TO 420
      WRITE(6,419)
  419 FORMAT(' ','THE SUBJECT HAD NO PRIOR TRACKING EXPERIENCE.')
      GO TO 422
  420 WRITE(6,421)
  421 FORMAT(' ','THE SUBJECT HAD PRIOR TRACKING EXPERIENCE.')
  422 IF(IP.GT.0) GO TO 424
```

```
***********************************************************************
*                                                                     *
*                      WRITE SUBROUTINE (CON'T)                       *
*                                                                     *
***********************************************************************

      WRITE(6,423)
  423 FORMAT(' ','THE SUBJECT HAD NO AVIATION EXPERIENCE.')
      GO TO 428
  424 IF(IP.GT.1) GO TO 426
      WRITE(6,425)
  425 FORMAT(' ','THE SUBJECT WAS A PRIVATE PILOT.')
      GO TO 428
  426 WRITE(6,427)
  427 FORMAT(' ','THE SUBJECT WAS A MILITARY PILOT.')
  428 IF(MM.GT.2) GO TO 430
      WRITE(6,429) XA,XD
  429 FORMAT(' ','THE INITIAL VALUE OF THE UNSTABLE POLE WAS ',F4.2,' RA
     1D/SEC.'/' ','THE RATE OF MOVEMENT OF THE UNSTABLE POLE WAS ',F4.2,
     1' RAD/SEC/SEC.')
  430 IF(NN.GT.100) GO TO 432
      Z=5.08/NN;WRITE(6,431) Z
  431 FORMAT(' ','THE QUANTIZATION LEVEL USED WAS ',F6.4,' CM.')
      GO TO 434
  432 WRITE(6,433)
  433 FORMAT(' ','NO QUANTIZATION WAS USED.')
  434 WRITE(6,435) KK
  435 FORMAT(' ','THIS WAS RUN NUMBER ',I2,' AT THIS QUANTIZATION LEVEL.
     1')
      IF(MM.GT.2) GO TO 437
      WRITE(6,436) X
  436 FORMAT(' ','THE CRITICAL INSTABILITY LEVEL WAS ',F8.5,' RAD/SEC.')
      GO TO 441
  437 WRITE(6,438) EM1,XI1,XX1,EE1
  438 FORMAT(' ','THE VERTICAL MEAN INPUT WAS ',F8.5,' CM.'/' ','THE VER
     1TICAL RMS INPUT WAS ',F9.5,' CM.'/' ','THE VERTICAL MEAN ERROR WAS
     1 ',F8.5,' CM.'/' ','THE VERTICAL RMS ERROR WAS ',F9.5,' CM.')
      IF(MM.EQ.4) WRITE(6,439) EM2,XI2,XX2,EE2
  439 FORMAT(' ','THE HORIZONTAL MEAN INPUT WAS ',F8.5,' CM.'/' ','THE H
     1ORIZONTAL RMS INPUT WAS ',F9.5,' CM.'/' ','THE HORIZONTAL MEAN ERR
     1OR WAS ',F8.5,' CM.'/' ','THE HORIZONTAL RMS ERROR WAS ',F9.5,' CM
     1.')
      IF(MM.EQ.5) WRITE(6,440) X
  440 FORMAT(' ','THE FINAL FILTERED VALUE OF THE CROSS-COUPLED'/' ',5X,
     1'INSTABILITY LEVEL WAS ',F8.5,' RAD/SEC.')
  441 RETURN
      END
```

```
******************************************************************
*                                                                *
*              SUBROUTINE TO FIND 5 SMALLEST VALUES              *
*                                                                *
******************************************************************

      SUBROUTINE SMALL(AA,LL,NN)
      COMMON XPOLE2(50),BPOLE(5),NUM(5),ERR(50),SERR(5),NERR(5),XERR1(5)
     1,XERR2(5),XXIN(5),XXIN2(5),XMIN(5),XMIN2(5),XERM1(5),XERM2(5)
      DIMENSION AA(50),CC(5),NN(5)
      DO 502 J=1,5
      CC(J)=AA(1)
      N=1
      MAX=LL-1
      DO 501 I=1,MAX
      IF(CC(J).LT.AA(I+1)) GO TO 501
      CC(J)=AA(I+1)
      N=I+1
  501 CONTINUE
      NN(J)=N
      AA(N)=999.0
  502 CONTINUE
      RETURN
      END
```

```
      ***************************************************************
      *                                                             *
      *              SUBROUTINE TO FIND 5 LARGEST VALUES            *
      *                                                             *
      ***************************************************************

      SUBROUTINE BIG(AA,LL,CC,NN)
      COMMON XPOLE2(50),BPOLE(5),NUM(5),ERR(50),SERR(5),NERR(5),XERR1(5)
     1,XERR2(5),XXIN(5),XXIN2(5),XMIN(5),XMIN2(5),XERM1(5),XERM2(5)
      DIMENSION AA(50),CC(5),NN(5)
      DO 602 J=1,5
      CC(J)=AA(1)
      N=1
      MAX=LL-1
      DO 601 I=1,MAX
      IF(CC(J).GT.AA(I+1)) GO TO 601
      CC(J)=AA(I+1)
      N=I+1
  601 CONTINUE
      NN(J)=N
      AA(N)=0.0
  602 CONTINUE
      RETURN
      END
```

```
      ******************************************************************
      *                                                                *
      *  SUBROUTINE TO FIND MEAN + STANDARD DEVIATION OF FIVE VALUES   *
      *                                                                *
      ******************************************************************

      SUBROUTINE AVRAGE(BB,AA,SS)
      COMMON XPOLE2(50),BPOLE(5),NUM(5),ERR(50),SERR(5),NERR(5),XERR1(5)
     1,XERR2(5),XXIN(5),XXIN2(5),XMIN(5),XMIN2(5),XERM1(5),XERM2(5)
      DIMENSION BB(5)
      AA=0.0;SS=0.0
      DO 701 J=1,5
      AA=AA+BB(J)
  701 CONTINUE
      AA=AA/5.0
      DO 702 J=1,5
      SS=SS+(AA-BB(J))**2
  702 CONTINUE
      SS=SQRT(SS/4.0)
      RETURN
      END
```

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DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

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2a. REPORT SECURITY CLASSIFICATION
Unclassified

2b. GROUP

T TITLE
Effects of Signal Quantization on Compensatory Tracking Performance

IPTIVE NOTES *(Type of report and inclusive dates)*
nautical Engineer (December 1972)

R(S) *(First name, middle initial, last name)*
er Michael Teichgraber

T DATE
ember 1972

7a. TOTAL NO. OF PAGES
103

7b. NO. OF REFS
6

RACT OR GRANT NO.

9a. ORIGINATOR'S REPORT NUMBER(S)

ECT NO.

9b. OTHER REPORT NO(S) *(Any other numbers that may be assigned this report)*

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Monterey, California

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he effects of quantizing the displayed error were investigated in single- and dual-axis critical compensatory tracking tasks and in ss-adaptive tracking tasks. Both first order and second order trolled elements were used, as well as an intermediate "1.5" er element. Quantization intervals investigated ran from 0 to 1.69 on a 10 cm by 10 cm display.

digital computer program was written for use with a hybrid puter in order to mechanize the various types of tracking tasks d in this research and for future use at this facility.

Results of the critical tracking task runs indicate that the operator's formance deteriorates almost linearly as the quantization interval ncreased. Cross-adaptive tracking task results indicate a pronounced rease in operator workload when quantization is used.

Security Classification

KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Quantization						
Critical						
Cross-Adaptive						
Compensatory						
Tracking						
Display						
Quantized						
Workload						
Excess Capacity						
Effective Time Delay						

Teichgraber
The effects of signal quantization on compensatory tracking performance.

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