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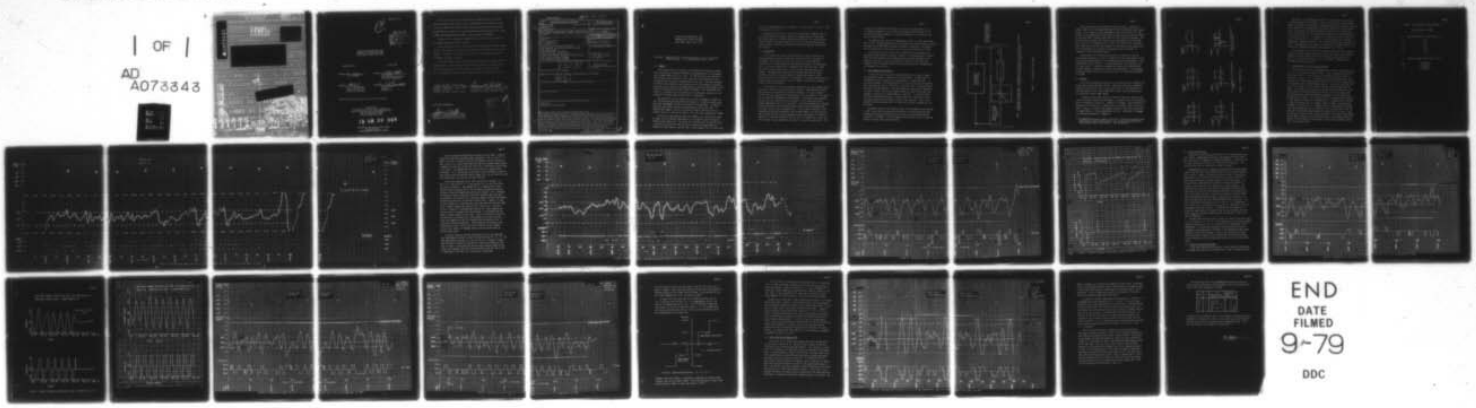

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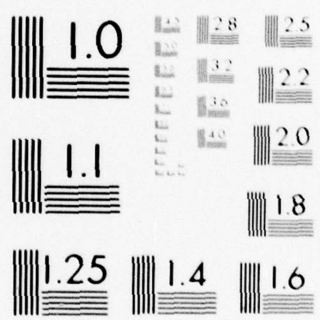

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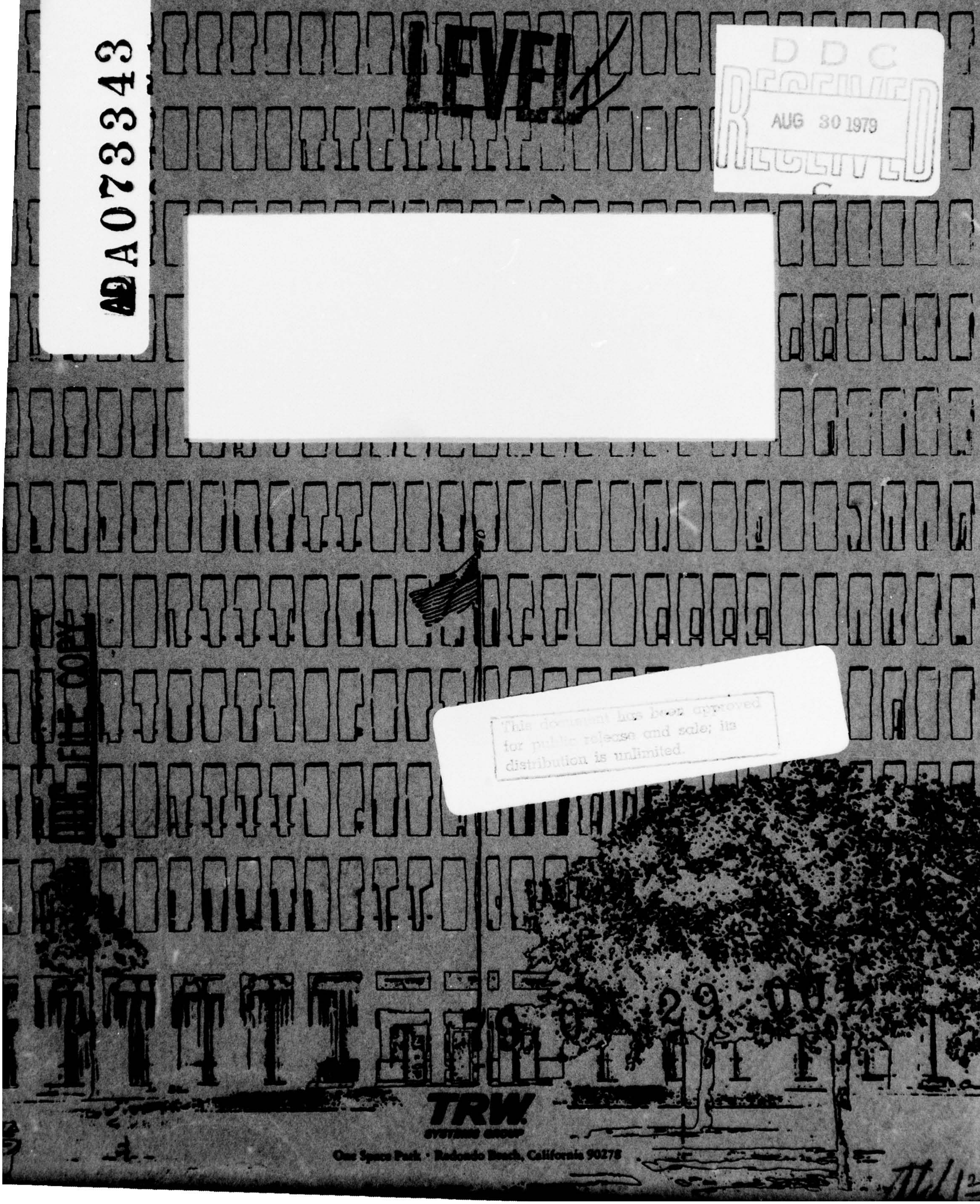

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SAMSO-TR-79-15

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FLIGHT-TEST EVALUATION OF ACM CONTROLLER AT 75RPM, ON SPACECRAFT 9433, APRIL 13-16, 1976

28600-AR-012-01

7 June 1976

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Captain G. D. Nordley, SAMSO/SKD, was the Project Officer for Space Communications Systems.

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This technical report has been reviewed and is approved for publication. Publication of this report does not constitute Air Force approval of the report's findings or conclusions. It is published only for the exchange and stimulation of ideas.

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This report presents an analysis, recommendations, and conclusions of flight data from Spacecraft #9433 taken during tests conducted following the implementation of the Automatic Control Mode (ACM) on April 13, 1976. The analysis had predicted that the tightest error control that could be hoped for at 75 RPM was approximately $\pm$ 2.5 degrees, and this was confirmed by the flight data. The final recommended gains at 75 RPM are a position gain "A" of 6 or 7, and a rate gain C of 0 to 8. General conclusion on the overall performance of ACM was that it can indeed maintain continuous control for longer periods of time than the normal mode.

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FLIGHT-TEST EVALUATION OF ACM CONTROLLER AT 75 RPM, ON SPACECRAFT 9433, APRIL 13-16, 1976

Reference: 28600-AR-011-01, "Design and Analysis of 777 'Fly-by-Wire' Control System," H. C. Osborne, dated 9 April 1976.

1.0 SUMMARY

This memo presents an analysis of flight data from Spacecraft #9433 taken during tests conducted following the implementation of the Automatic Control Mode (ACM) on April 13, 1976. The ACM controller was designed to send commands from the ground to the spacecraft using proportional plus derivative control based on telemetered position data. The main advantage of ACM was not intended or even expected to be an improvement in pointing accuracy, but was instcad to provide automatic recovery from periods of lost earth lock during times of high torque disturbance. The normal mode controller is incapable of such performance, and continuous operation of the spacecraft in normal mode at these times is impossible.

The purpose of the test period was to verify that ACM can indeed control the spacecraft, and to optimize performance at 75 RPM by varying gains about the recommended settings as provided by the Reference. Included in the tests were cases in which only proportional control was used. In addition the command limit was increased for some of the tests from its nominal value of ± 1 count to ± 2 counts. All tests were conducted at 75 RPM.

The analysis had predicted that the tightest error control that could be hoped for at 75 RPM was approximately $\pm$ 2.5 degrees, and this was confirmed by the flight data. The tests also confirmed that the position gain is the more significant of the two gains in determining amplitude and frequency of the response, and that the ± 1 count command limit is sufficient.

The final recommended gains at 75 RPM are a position gain "A" of 6 or 7, and a rate gain C of 0 to 8.

The general conclusion on the overall performance of ACM was that it can indeed maintain continuous control for longer periods of time than the normal mode, but if normal mode can be maintained it is the preferred state because of the higher degree of accuracy. Also even ACM was occasionaly unable to recover the spacecraft and ground operator intervention was required.

2.0 INTRODUCTION

The 777 Spacecraft #9433 normal mode despin control system was originally designed to point the platform to the earth with an accuracy of .15 degree. During the past year, much larger excursions have been observed, and in recent months the excursions have been of such magnitude so as to cause the spacecraft to frequently lose lock with earth. When this occurs, normal mode control is lost and the spacecraft goes into standby. Recovering the spacecraft from standby mode requires ground operator intervention and often takes a considerable amount of time, during which use of the satellite is precluded. It was thus desired to find a way to operate the spacecraft in such a manner so that more continuous control could be maintained.

In an effort to solve this problem, TRW Defense and Space Systems Group was given a contract by the Air Force to develop a system whereby recovery from periods of lost earth lock would be automatic. In such a system, nearly continuous operation of the spacecraft could be achieved. The results of this study are documented in the Reference. Very briefly, the proposed design calls for operation of the spacecraft in the search mode with a ground commandable loop to the spacecraft. The ground commands are computed using proportional plus derivative control based on the telemetered position data, and are sent up automatically. In this mode of operation, subsequently designated the Automatic Control Mode (ACM), it was realized that the pointing accuracy would be degraded, but the advantage of this type of operation is that the controller will not "quit" if earth lock is lost, but will continue issuing commands to the motor to recover the spacecraft. The accuracy to be expected from ACM was predicted to be approximately ±1 to 2.5 degrees, depending on spin speed, and although this precludes use of the narrow coverage antenna, it is more than adequate to allow use of the earth coverage antenna.

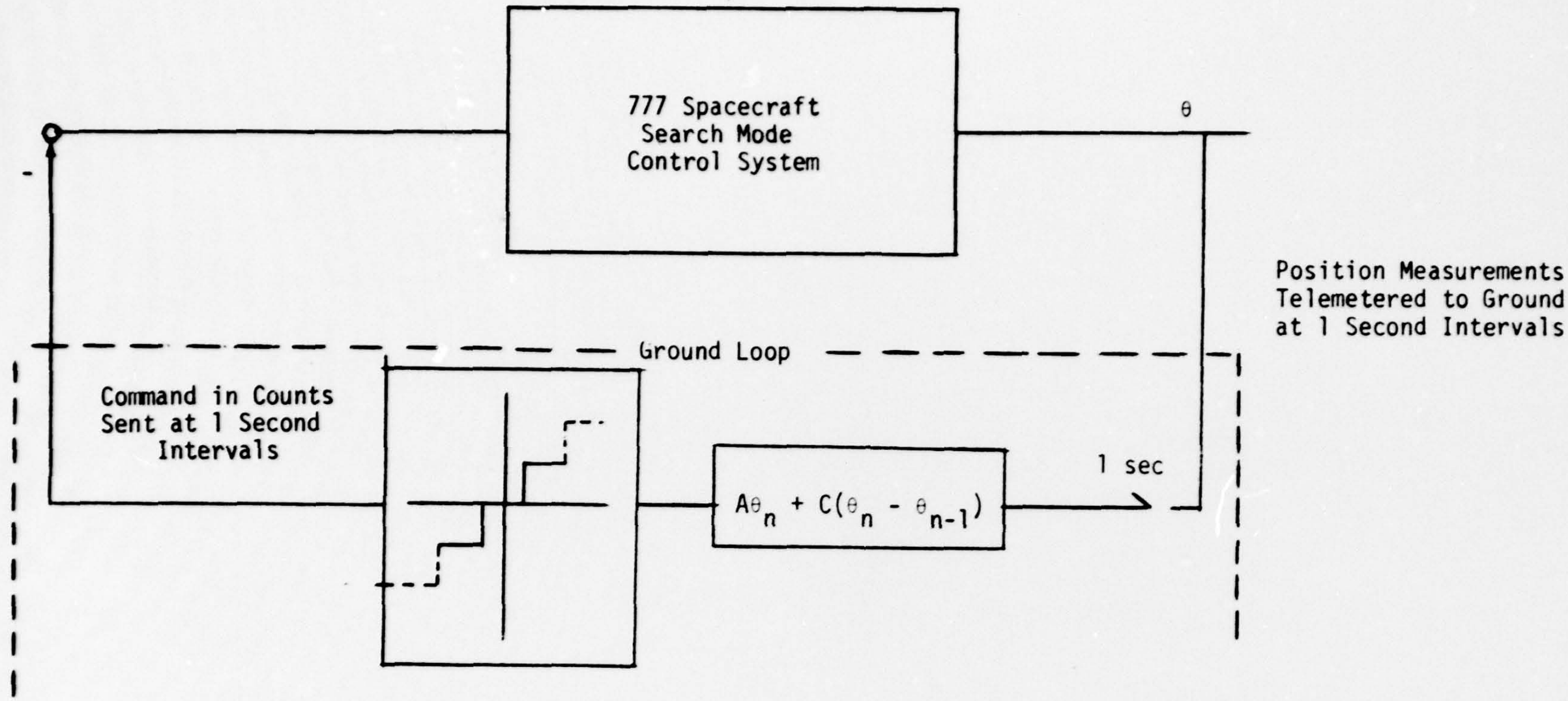
The ACM controller was first implemented on April 13, 1976, and tested April 13-16. Although the analysis had indicated that better accuracy could be obtained at the lower RPM (±1 degree at 40 RPM) a reduction in spin speed was not authorized for the tests, so all tests were conducted at 75 RPM.

In the next sections, the results of these tests are presented, and compared with the predicted results. Section 3 is concerned with a slightly more detailed explanation of the ACM controller and the parameters to be studied in the tests, Section 4 presents the results of the tests and compares them to simulated results, and the conclusions and recommendations are presented in Section 5.

3.0 ACM CONTROLLER DESCRIPTION

A simplified block diagram of the ACM controller is shown in Figure 1. The spacecraft itself is operated in the search mode. Position data is telemetered from the spacecraft to the ground at 1 second intervals. In the ground computer, the position gain "A" is used to multiply the position data, and the rate gain "C" multiplies the derived rate. The sum of these two terms forms the command. Since the spacecraft receives the commands in the form of counts, and only an integer number of counts can be sent, the command is converted to a whole number by round-off. It should be noted that the resulting quantization is rather large and in fact only 1 count in either direction is necessary to control the spacecraft. Thus in the nominal design the command block is limited to ±1 count, although this can be varied.

One other aspect of the controller that is not evidenced by the diagram is that if more than 60 consecutive data points are received outside the scanned earth chord (corresponding to 1 minute of invalid data), the ACM controller is disabled. This was judged to be sufficient time to allow the system to recover from large transients.



Note: Time between instant when θ telemetered from spacecraft, to the receiving of ground command by the spacecraft is estimated at 2-6 seconds, depending on RPM.

Figure 1. 777 Automatic Control Mode

The accuracy that can be expected from this system is necessarily rather crude, due to the large quantization effect introduced by the ground counter, and is almost entirely dependent on the position gain "A".* The analysis of the Reference had shown that the best accuracy could be achieved at the lower RPM's, because higher position gains could be tolerated. The position gains selected were roughly 1 count per degree error at 40 RPM and 1 count per 2.5 degree error at 75 RPM. The analysis also indicated that inclusion of the rate term produced little effect on the steady state error performance, but did result in somewhat smaller transients in response to large disturbance torques.

The purpose of the testing period on April 13-16 was to vary the position and rate gains "A" and "C" respectively, from these nominal values as provided by the Reference, in an attempt to optimize performance. Both proportional control only ("C" = 0) and proportional plus derivative control were tried. In addition, although the analysis had indicated that ±1 count should be sufficient to control the spacecraft, a 5 step command block with counter limits at ±2 was also tried. All tests were conducted at 75 RPM.

4.0 RESULTS

This section presents the results of the flight tests and compares the actual data to the simulation results. There were three basic parameters that were varied in the tests - the position gain "A", the rate gain "C", and the counter limits. Both proportional control only and proportional plus derivative control were tested.

In order for the reader to gain an intuitive idea as to how the variation of the gains affect the performance, a "typical" plot of the pointing error is sketched in Figure 2-a. Suppose, for example, a position gain "A" equivalent to 1 count per 1.5 degree error is selected. Then if the rate gain "C" were 0, as soon as the computer received a data point outside the 1.5 degree band, a 1 count command would be sent. Increasing "A" narrows the band and decreasing "A" widens it.

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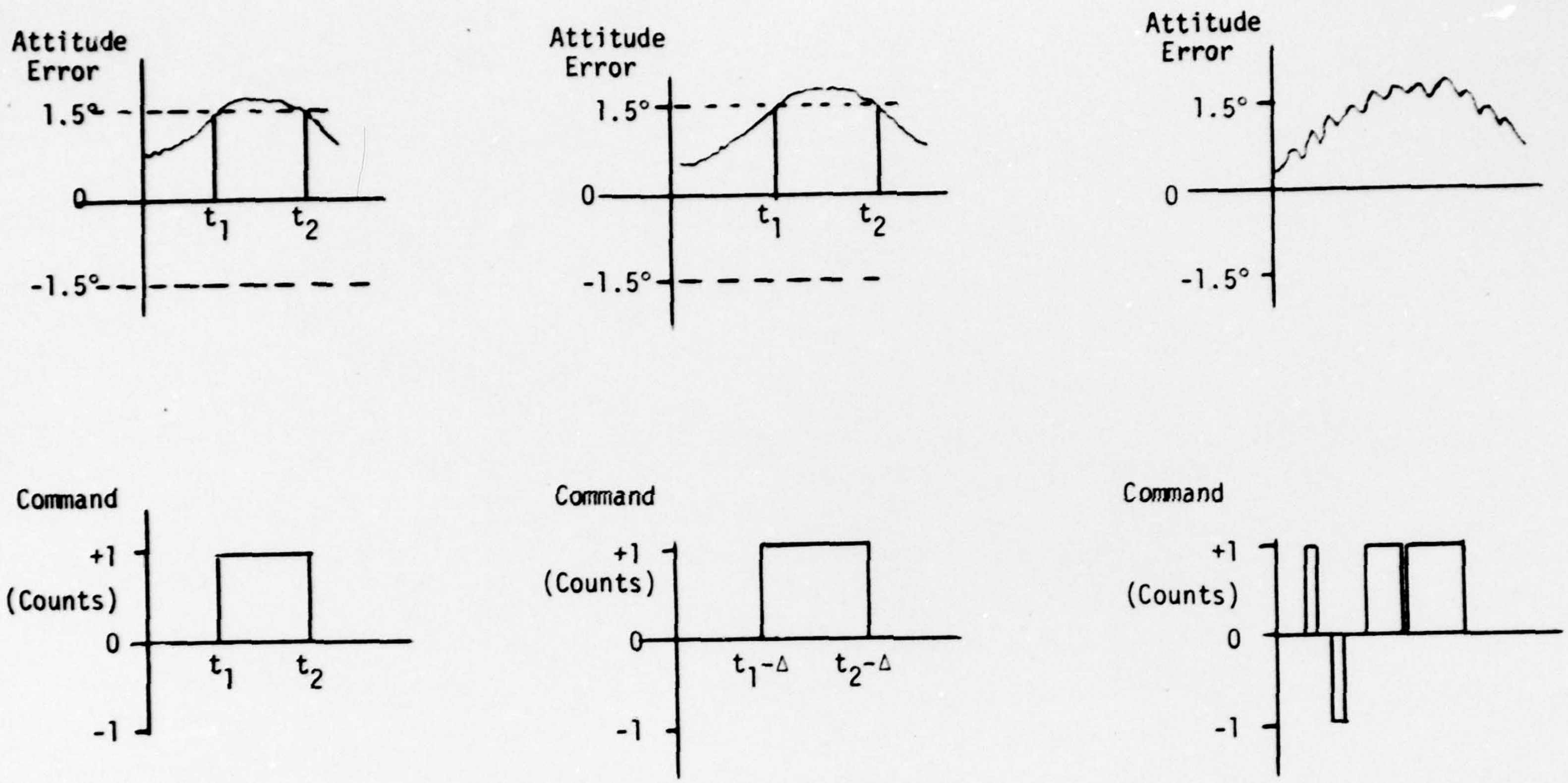
* It should be mentioned, however, that even if there were no ground loop quantization, counter quantization in the spacecraft rate loop would limit accuracy, to a certain extent. See the Reference.



2-a. Proportional Control Only

2-b. Proportional Plus Derivative Control

2-c. Effect of High Rate Gain "C" With "Noisy" Data

Figure 2. ACM Control Law

The effect of including a rate term "C" (see Figure 2-b) is to add a prediction term to the command, so that 1 count will be issued slightly sooner (Δ seconds) if the error is increasing toward the 1.5 degree mark, and once issued, will be removed before the error decreases to the 1.5 degree point. This effect is almost impossible to discern on the flight data plots, but the rate term can have another effect that is very readily seen. If the position data is not "smooth" as in Figures 2-a and 2-b, but has a lot of "hash" in it, as in Figure 2-c, a high rate gain can cause many unnecessary commands to be sent. Thus one indication of how much the rate term is contributing to the command is how often the command changes in or outside the "bounds" determined by the position gain "A" alone.

The remainder of this section is devoted to the study and interpretation of the actual flight data as the gains A and C were varied, and the command limit was changed. The first test done was with the position gain A at its nominal setting of 6, or 1 count per 2.3 degree error (75 RPM) and varied rate gains.

4.1 Position Gain "A" at 6, Varied Rate Gain

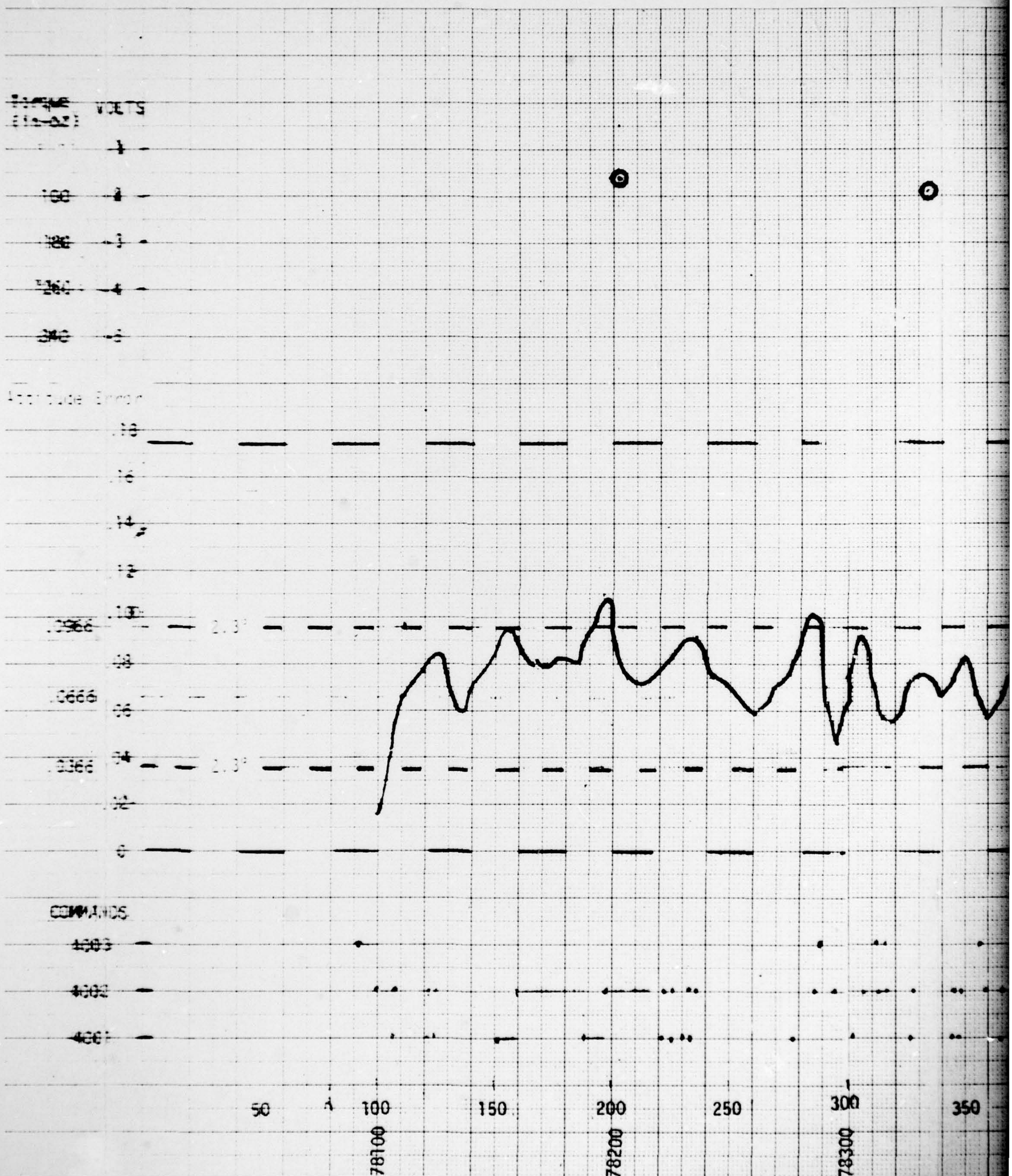
The nominal position gain recommended for 75 RPM in the Reference was "A" = 6, or 1 count per 2.3 degree error. (For an interpretation of the gains, see Table I.) The first test of the ACM controller on April 13 was with A = 6 and C = 36. Simulation results had predicted that a position gain of 6 should keep the pointing error to within ±2.3 degree except in the presence of large disturbance torques. The actual flight data for this case is shown in Figure 3 along with the torque voltages and commands. The 0 degree line and the ±2.3 degree lines are indicated on the plot as well as the places where the platform lost lock with the earth. The pointing error generally behaved as expected, but the command rate proved to be very high. For the data plotted, 128 commands were observed in 950 seconds, resulting in a command rate of 1 command every 7 seconds. In some time periods (see for example, 78300 to 78400) 25 commands were recorded in 100 seconds, for a command rate of 1 command every 4 seconds. This rapid command rate was an indication that the rate term "C" was too high, not from stability considerations but because of the "hash" in the pointing error due to smaller torque variations. These small disturbances had not been simulated in the Reference because of the inavailability of typical friction data which was supposed to have been provided to TRW as part of the design effort.

Table I. Position Gain A and Rate Gain C

Position Gains (75 RPM)

A	Degree Error When 1 Count Sent, if C = 0
5	2.75°
6	2.3°
7	2.0°
8	1.72°
9	1.53°

C	Rate Error When 1 Count Sent, if A = 0
36	.38 deg/sec
12	1.14 deg/sec
6	2.29 deg/sec


VOLTS
100
Attitude Error
.18
.16
.14
.12
.10
.0966
2.3°
.08
.0666
.06
.0366
2.3°
.04
.02
0
COMMANDS
4003
4002
4001
50
100
150
200
250
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350
78100
78200
78300

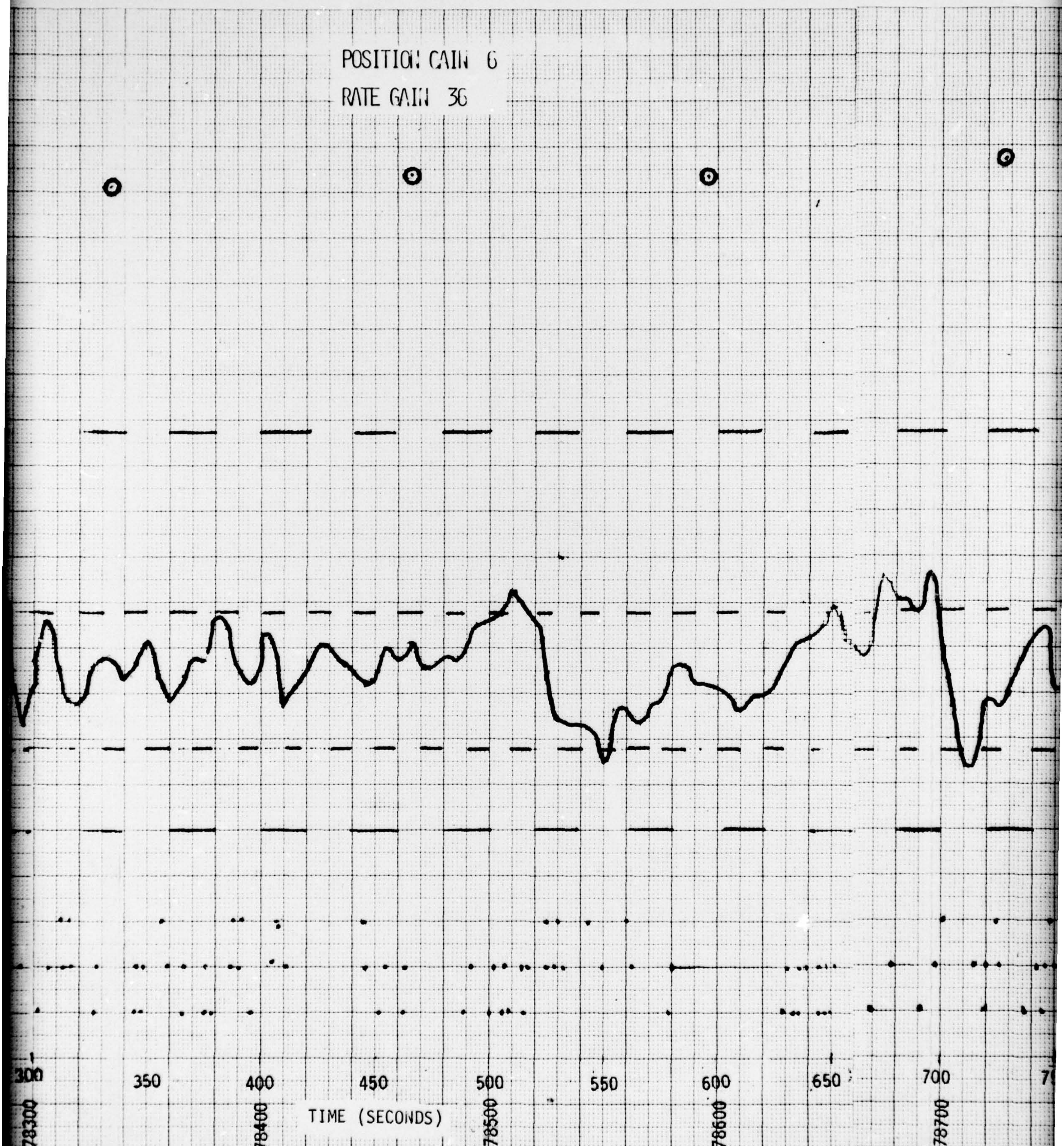
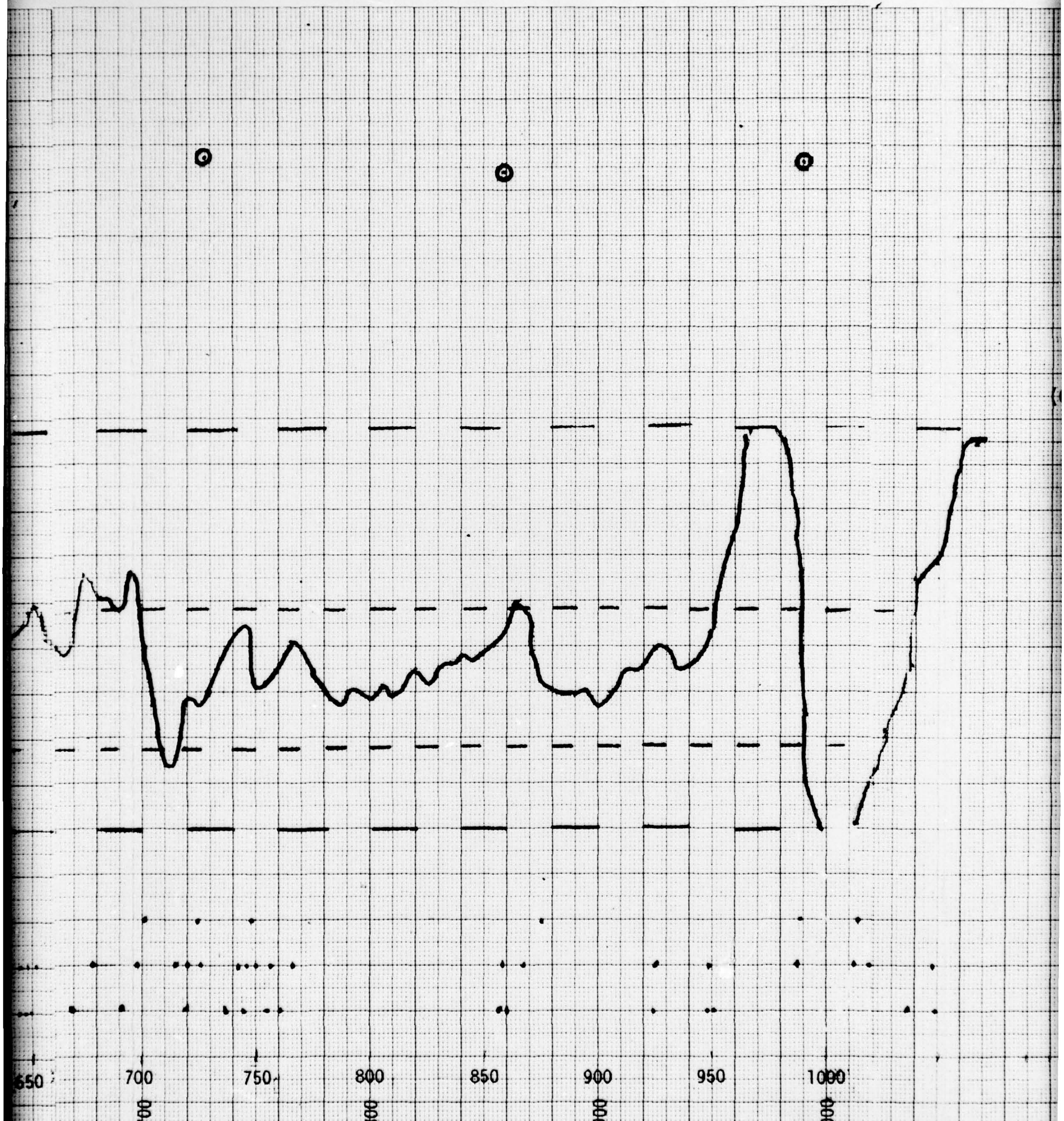


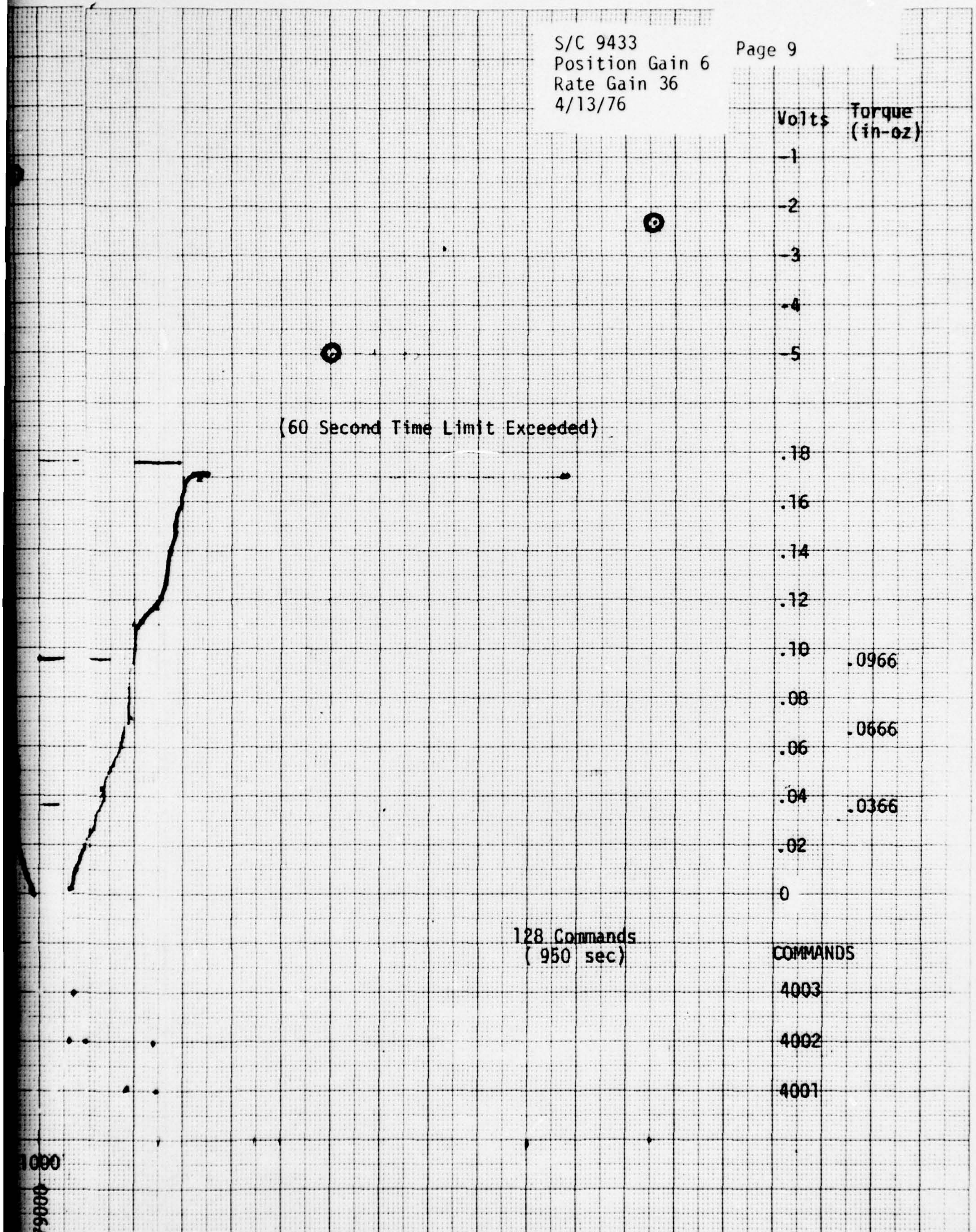
Figure 3. Attitude Error Versus Time for A = 6, C =

2



ersus Time for A = 6, C =36, 75 RPM (April 13, 1976)

3


S/C 9433
Position Gain 6
Rate Gain 36
4/13/76
Page 9
Volts
Torque (in-oz)
-1
-2
-3
-4
-5
(60 Second Time Limit Exceeded)
.18
.16
.14
.12
.10
.0966
.08
.0666
.06
.04
.0366
.02
0
128 Commands (950 sec)
COMMANDS
4003
4002
4001
4000
79000

For the second test proportional control only was tried. Figure 4 shows the flight data resulting under conditions as "A" = 6 and "C" = 0. Again, the error is generally within ± 2.3 degrees, and with a position term in only, it is easily seen that once the error exceeds these bounds, a command is given and is held until the error is brought to within these limits again. The command rate for this period was 1 command every 33 seconds. It is interesting to note that little difference is seen in the pointing error performance itself between this case and the first one, even though the first case had the high rate gain.

It was then suggested that a small rate gain be included. On April 15, a rate term of "C" = 8 was tested ("A" = 6) and the results are shown in Figure 5. The command rate is 1 command every 10 sec. (Notice that the command rate is fairly steady throughout the period plotted, unlike the command rate in Figure 3, where C = 36.) Although the technical staff at the test center had indicated that from their observations, the inclusion of a rate term seemed to improve performance, no definite conclusions can be made from this data. However, it does no harm to keep it in, and the only result observed from the data seems to be a higher command rate then with no C term at all. Even this result is subject to interpretation, because the higher command rate could be due to increased torque disturbances, as evidenced from the higher voltage readings on this date. Also, an indication of how much the rate term is contributing to the commands can be seen from how often the commands are sent (or changed) when the pointing error is inside the indicated boundaries. (The boundaries define when a command should be sent if only the A term is present in the command.) In this case, almost all commands seem to also have been given by position data alone.

A typical response from the simulation results of the pointing error performance is shown in Figure 6 (Position Gain "A" = 6, "C" = 0). (The disturbance torque was 10 in-oz for 20 sec.) Although it might seem difficult to perceive a similarity in this case, because of the lack of "hash" in the simulation results, what should be noted is the rather low frequency with which the error drifts from one side of the 2.2 deg bound to the other, as in the actual flight data.

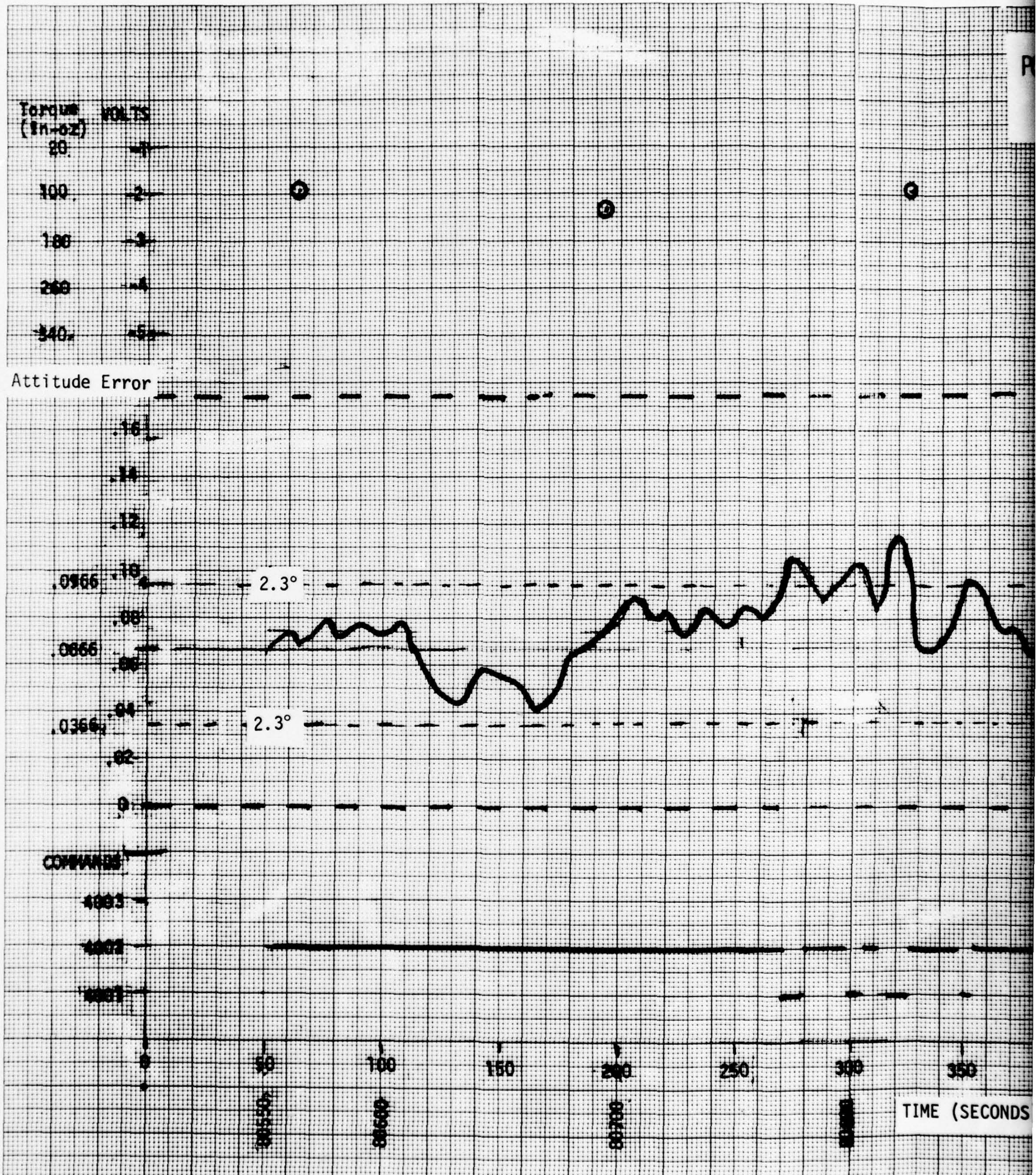
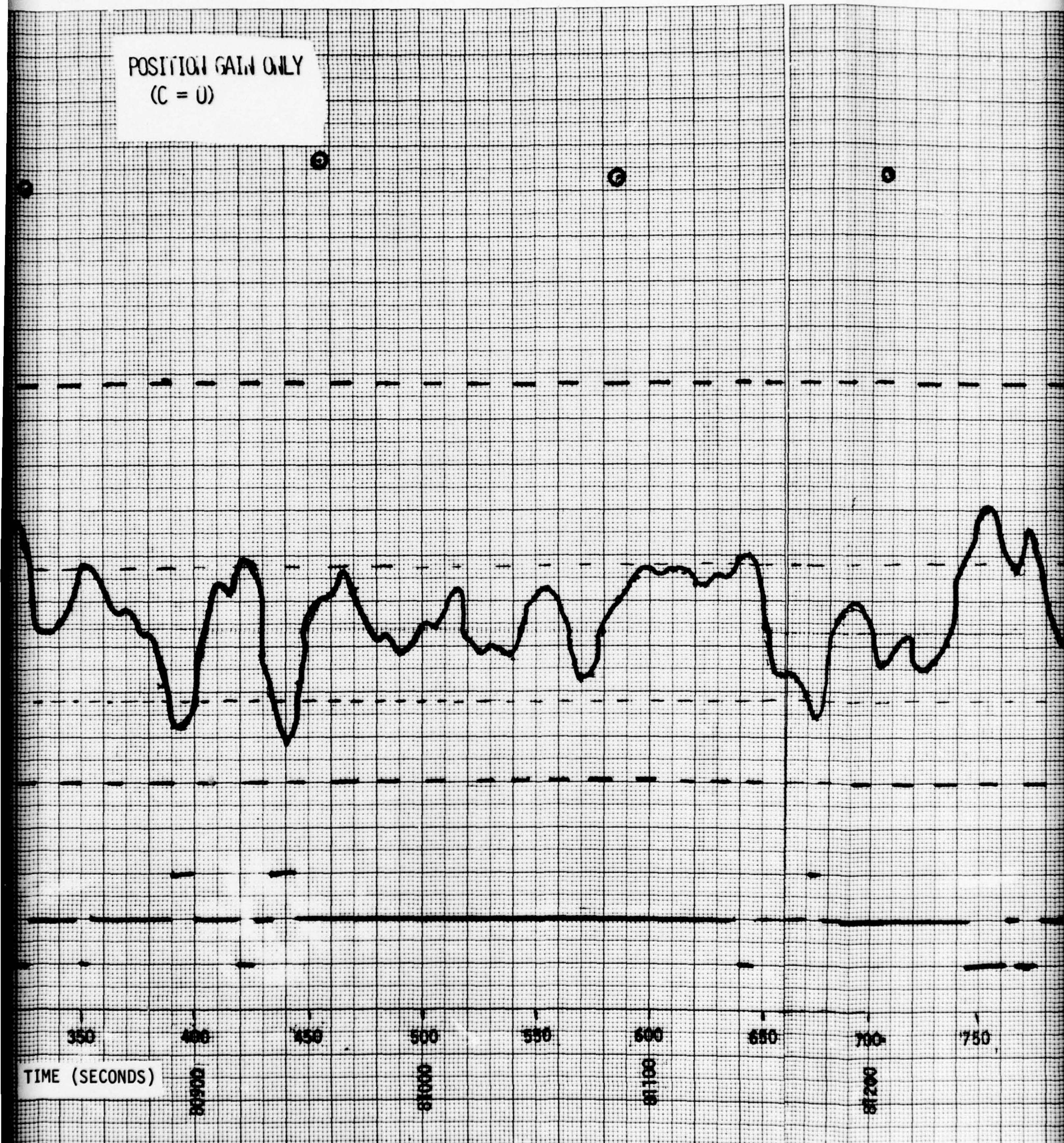


Figure 4. Attit



gure 4. Attitude Error Versus Time for A = 6, C = 0 , 75 RPM (April 13, 1976).

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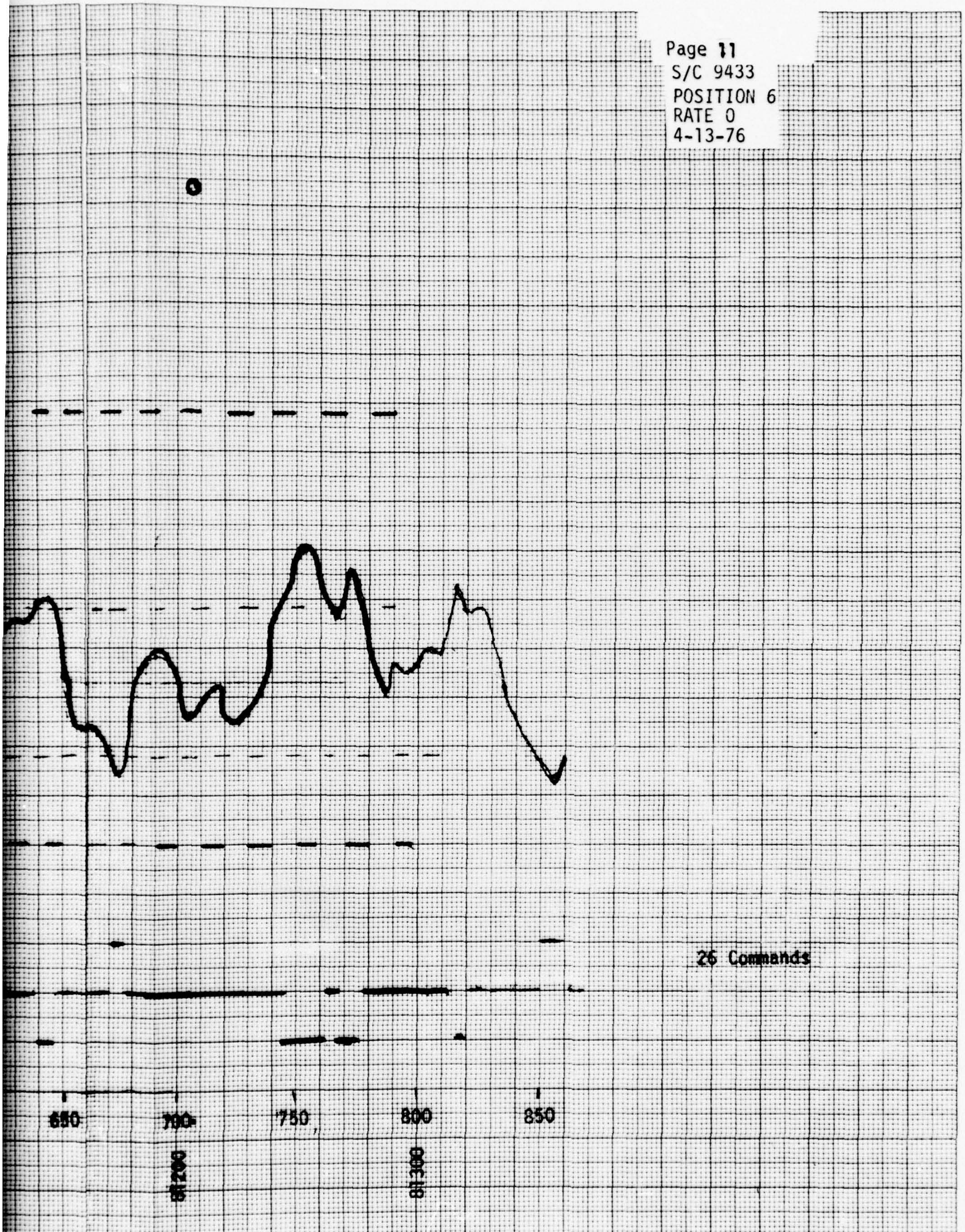

Page 11
S/C 9433
POSITION 6
RATE 0
4-13-76
26 Commands
650
700
750
800
850
81200
81300

1976).

3

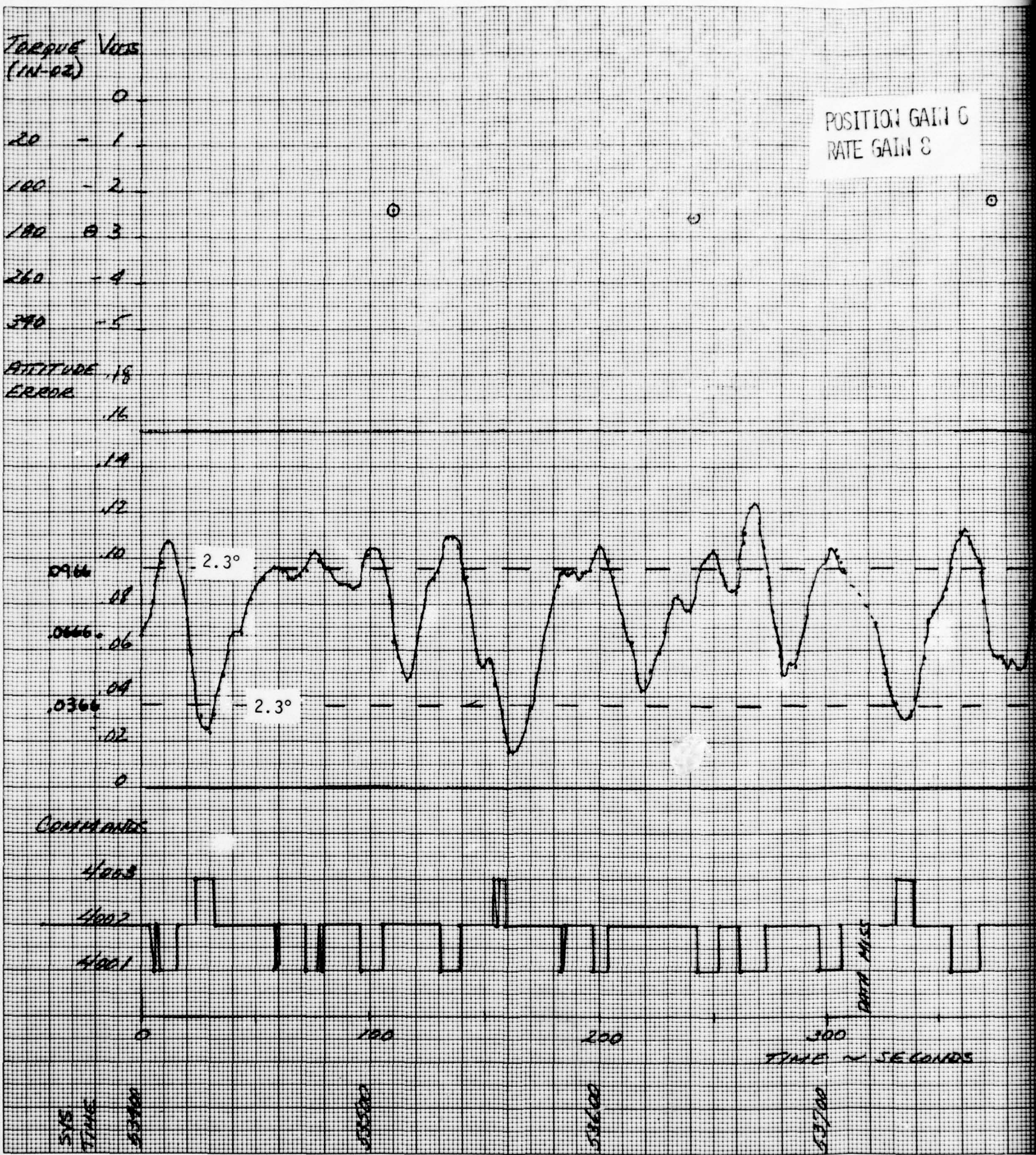
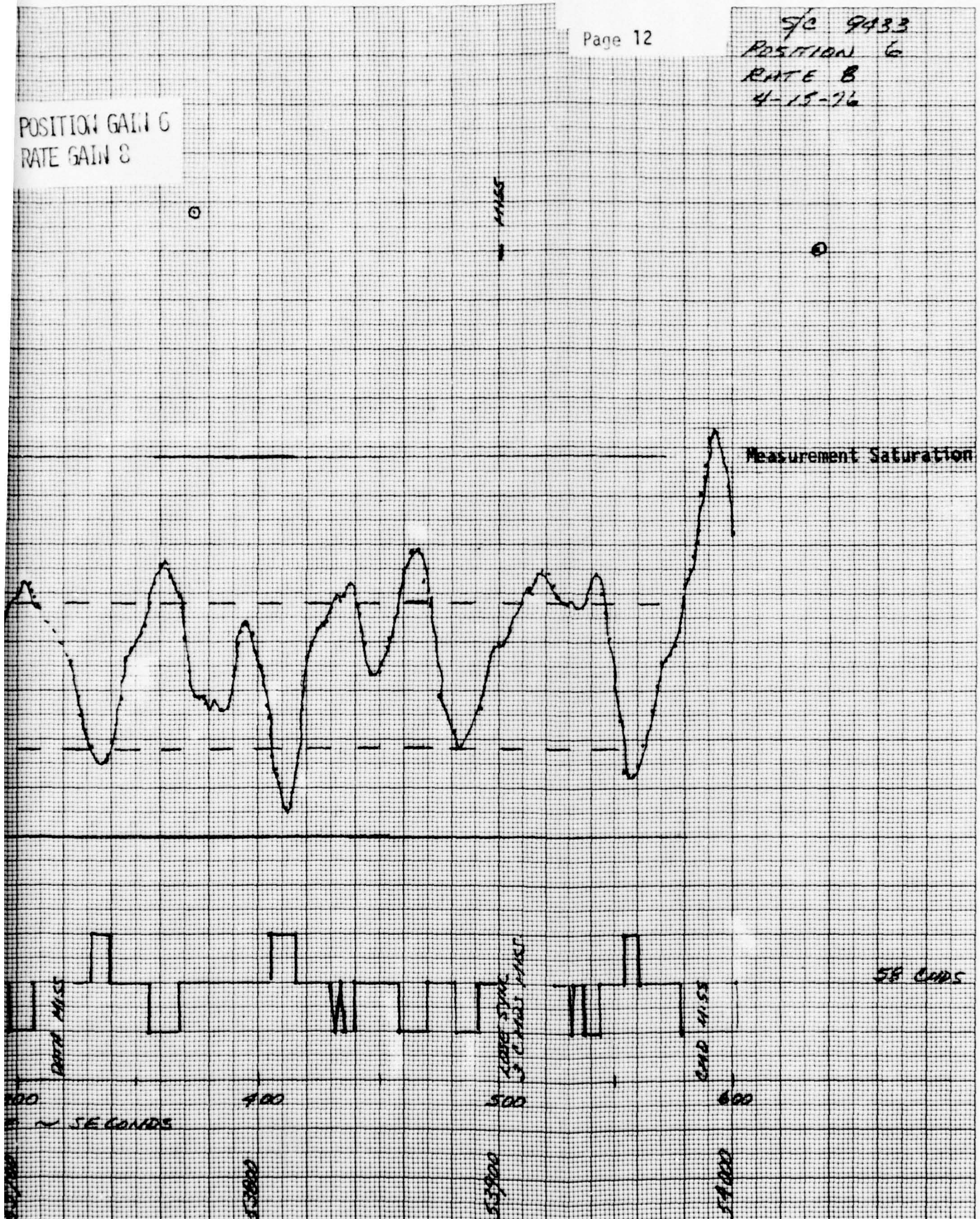


Figure 5. Attitude Error Versus Time for A = 6, C =



...us Time for A = 6, C = 8, 75 RPM (April 15, 1976)

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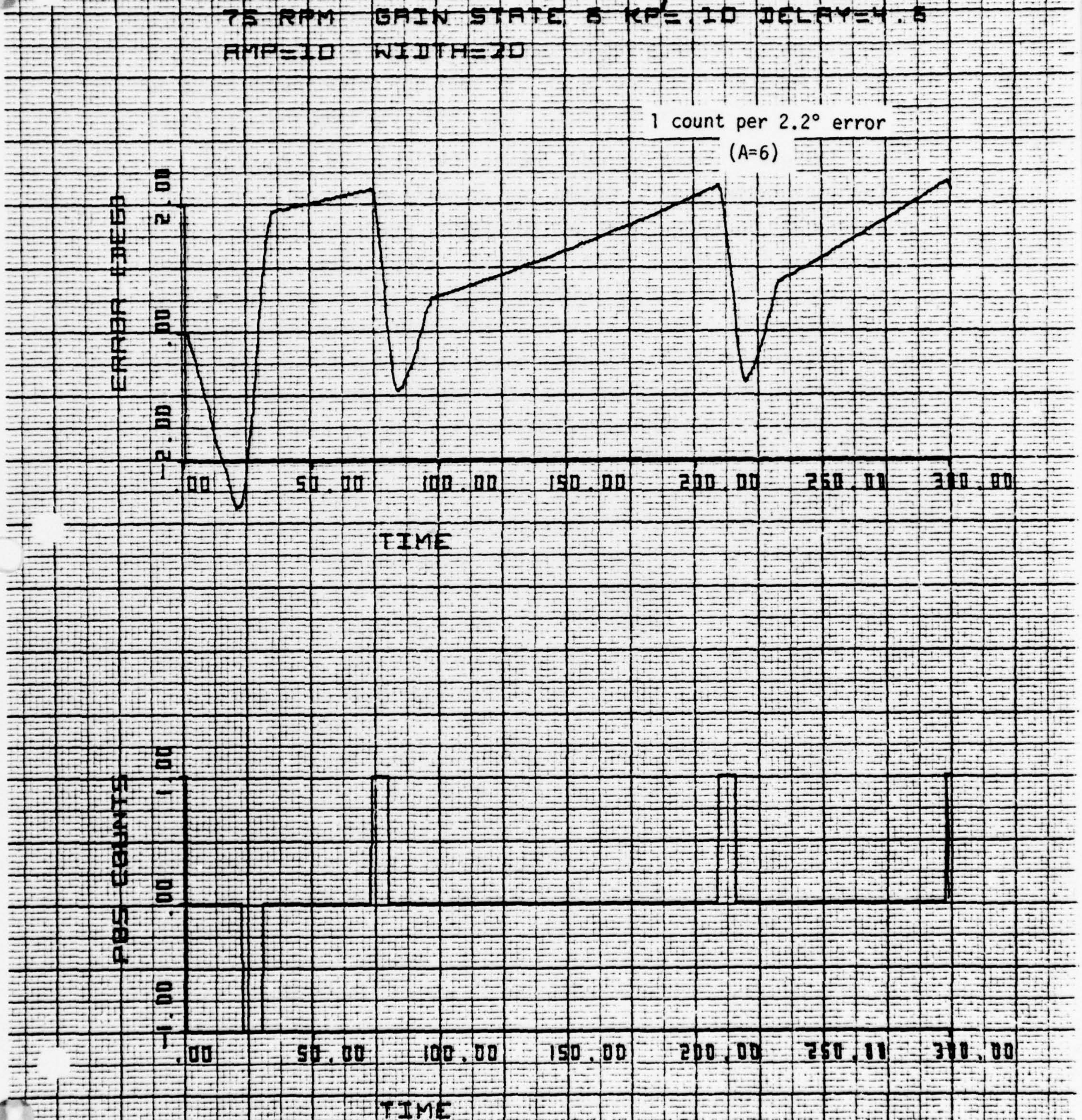


Figure 6. Simulation Response of ACM Control System at 75 RPM (A = 6, C = 0)

3.2 Varied Position Gain

The effect of varing the position gain "A" on the performance was also studied. Decreasing the position gain widens the band around 0 deg, and results in a generally sloppier performance. A position gain of 5 was tried, which resulted in 1 count per 2.75 deg error. The pointing error data for this case is shown in Figure 7.

Increasing the gain "A" narrows the band around 0 deg and causes counts to be sent more often as the system tries to maintain tighter error control. However, increasing the gain results in improved performance only up to a point, and after that, a further increase in gain causes the system to become unstable in the linear sense. In the non-linear system where the counter is limited, the effect is simply to drive the error back and forth at a high frequency. The fact that the system is being driven is evidenced by observing that counts are first issued in one direction and then in the other, with very little time at 0 count. In fact, the analytical results (Reference) had predicted that at 75 RPM, a position gain of about 6 or 7 was the maximum that could be tolerated before this would occur. Figures 8 and 9 which have gains of "A" = 9 and "A" = 12, respectively (or 1 count per 1.5 deg error and 1 count per 1.1 deg error), show this phenomenon (simulation results). (It should also be noted that in these two cases, where an "unstable" gain has been selected, the peak errors cannot be predicted from the gains--here peaks of 2 deg and 3 deg were obtained.)

Figures 10 and 11 show the actual flight test data for position gains of "A" = 8 and "A" = 9. At "A" = 8 the frequency of oscillations becomes slightly higher than at "A" = 6, and there is no improvement in error performance. In Figure 10, the system is definitely being forced as evidenced by the banging back and forth of the commands and the higher frequency of the error response. (Here, since the system is being driven, the small random friction fluctuations are not as noticeable in the flight data, and the flight data looks more like the simulation data.)

3.3 Effect of Varying the Counter

It had been speculated that perhaps 2 counts might be better than 1, although the analysis had indicated that 1 count in either direction

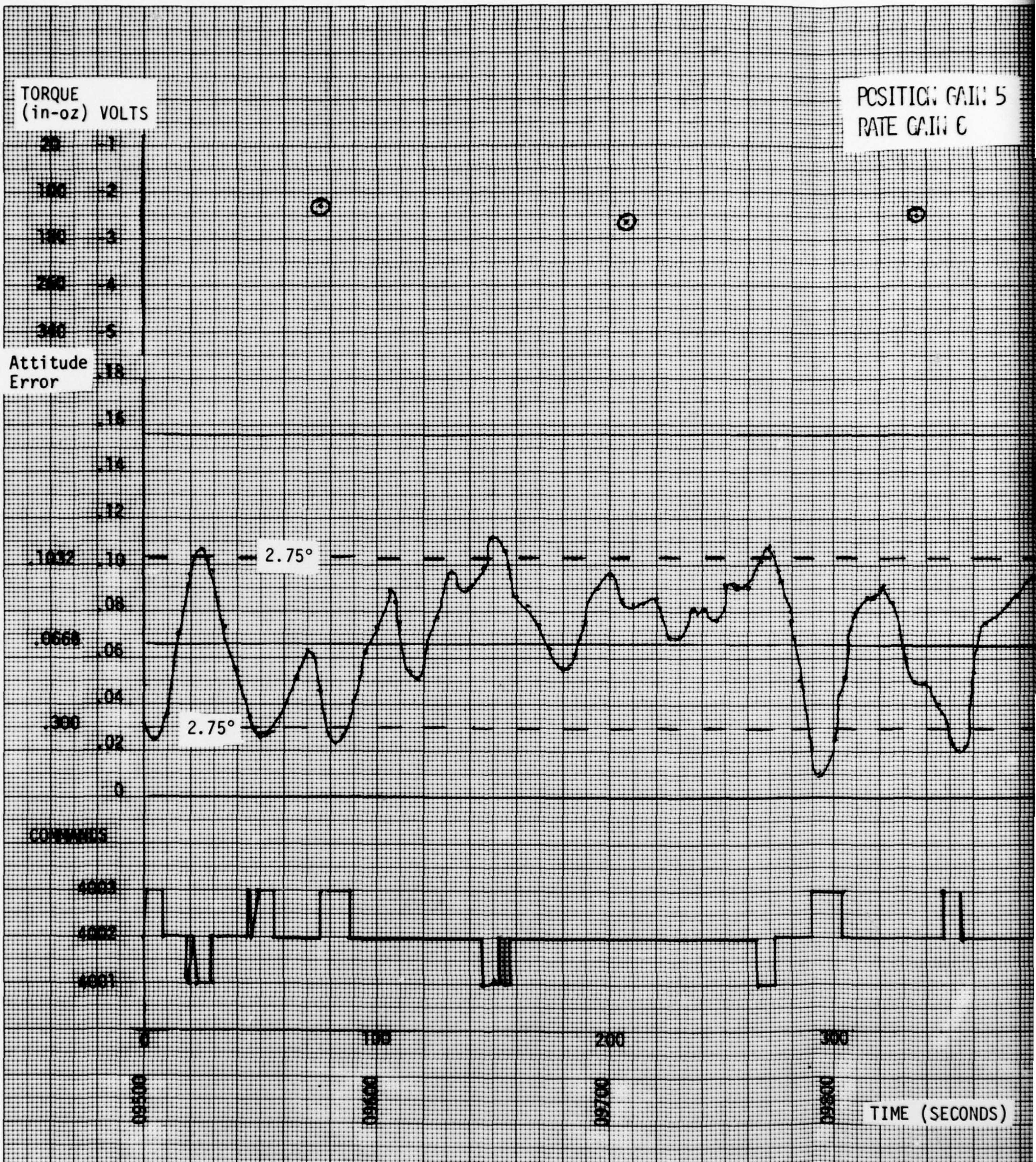
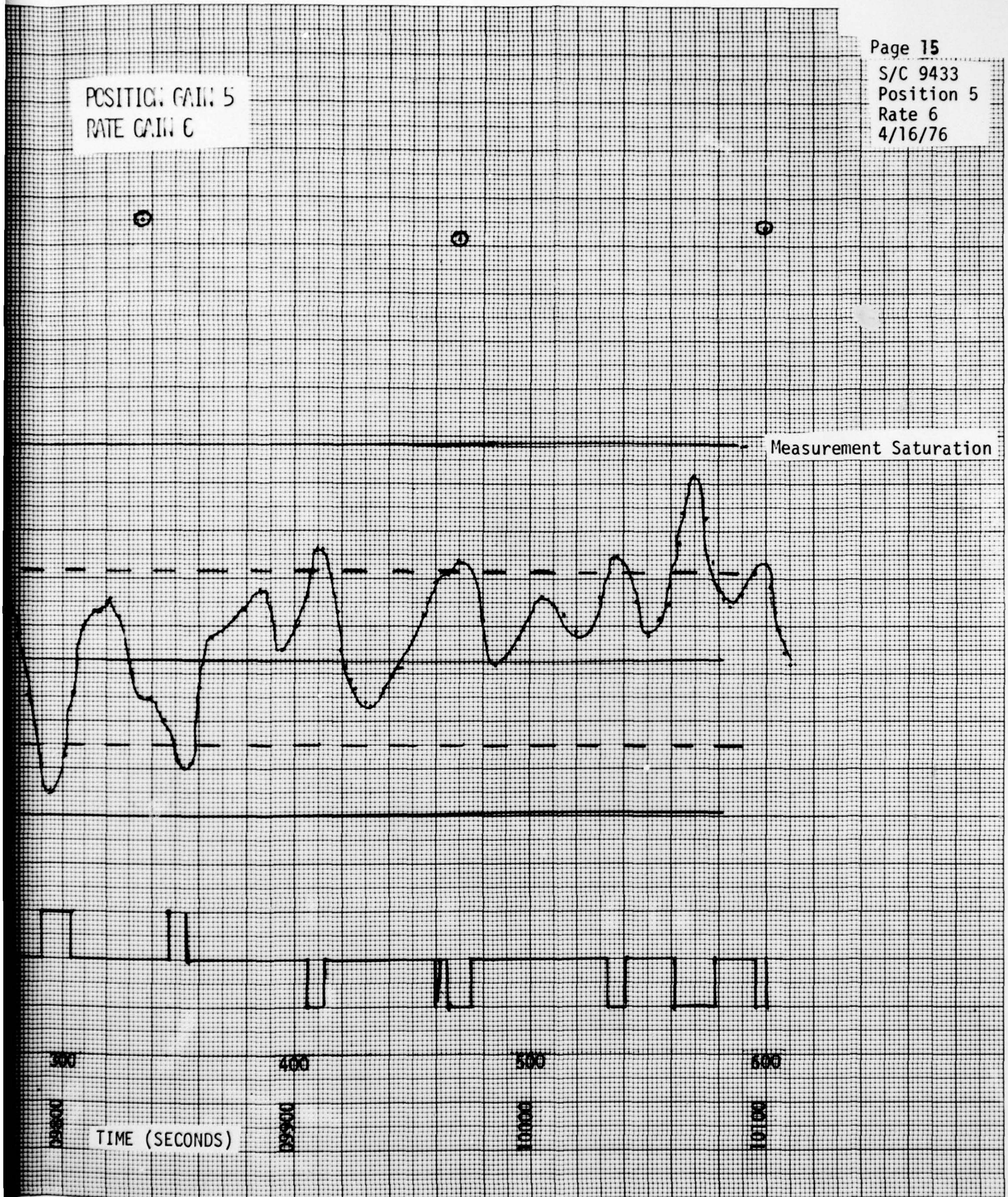


Figure 7. Attitude Error vs Time for A = 5, C = 6



vs Time for A = 5, C = 6, 75 RPM (April 16, 1976)

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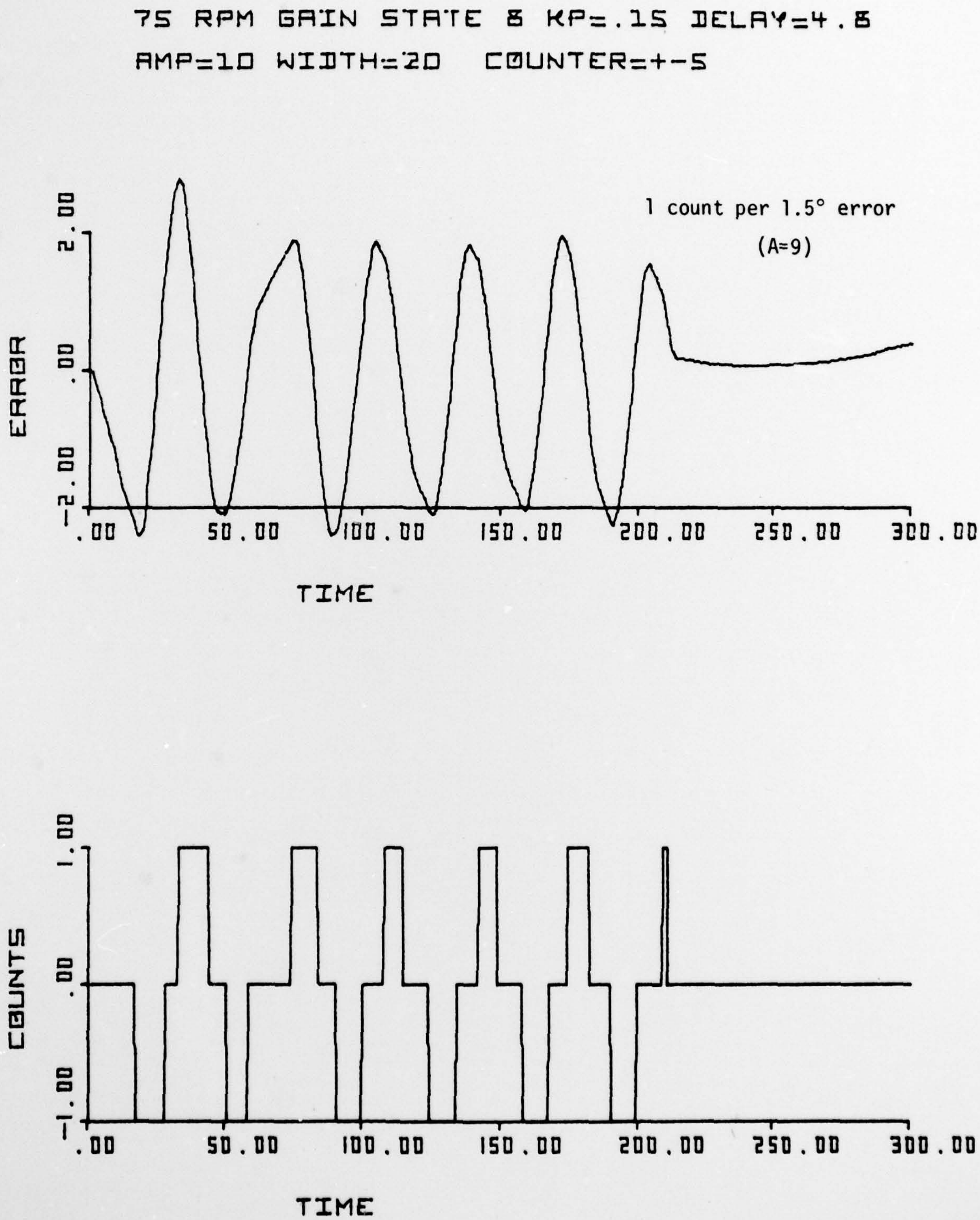


Figure 8. Simulation Response of ACM Control System at 75 RPM (A = 9, C = 0)

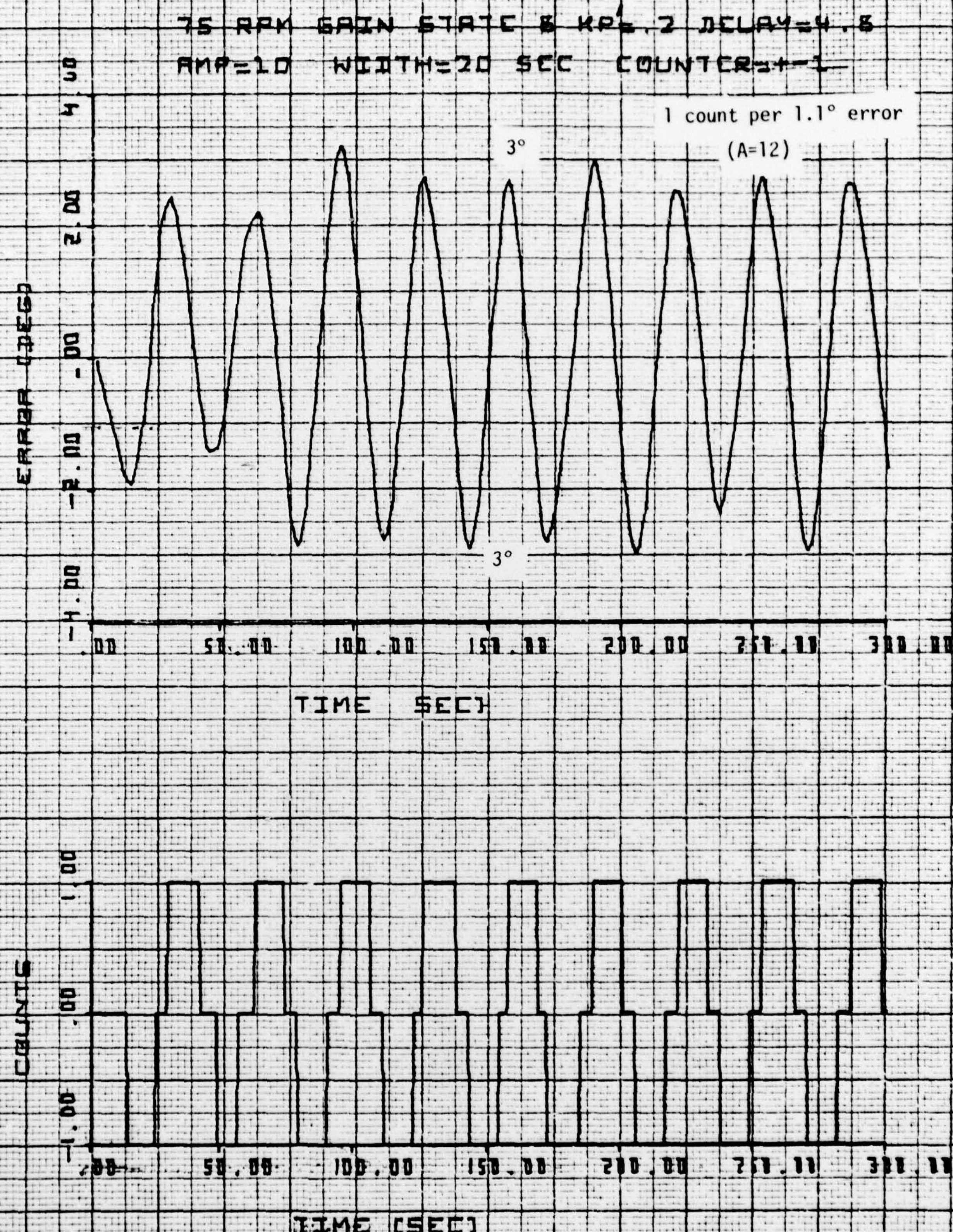


Figure 9. Simulation Response of ACM Control System at 75 RPM (A = 12, C = 0)

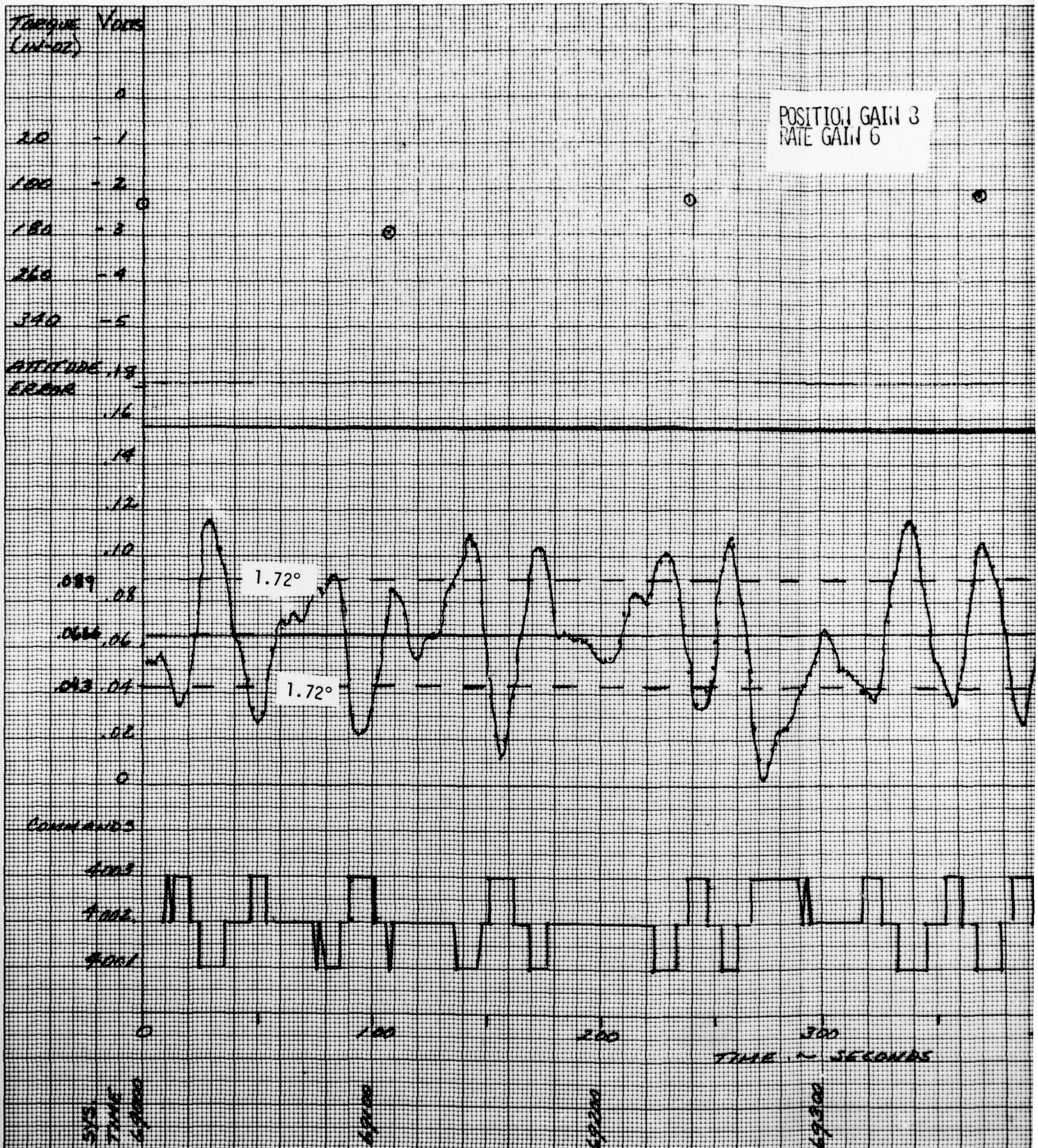
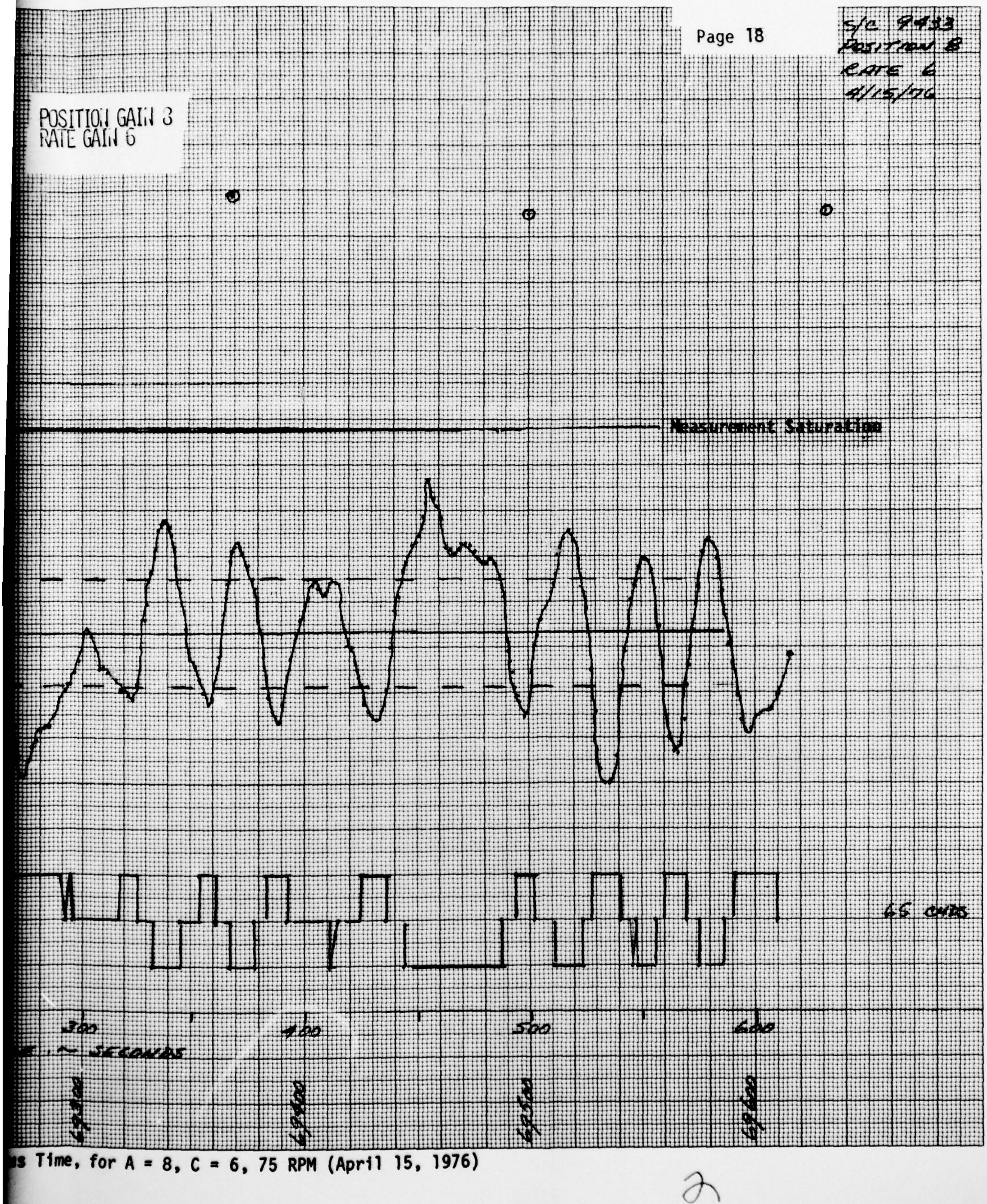


Figure 10. Attitude Error Versus Time, for A = 8, C = 6, 75



...s Time, for A = 8, C = 6, 75 RPM (April 15, 1976)

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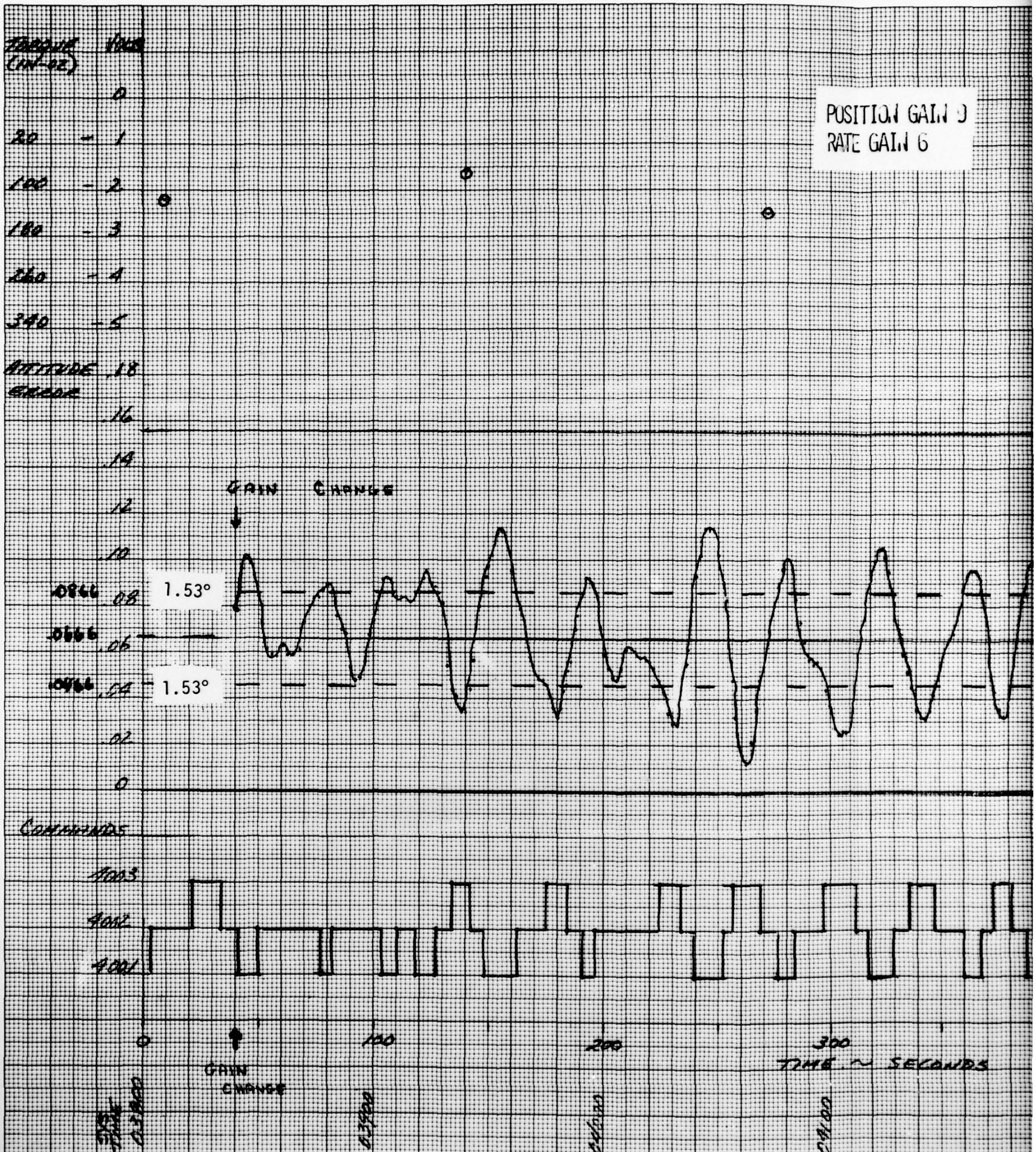
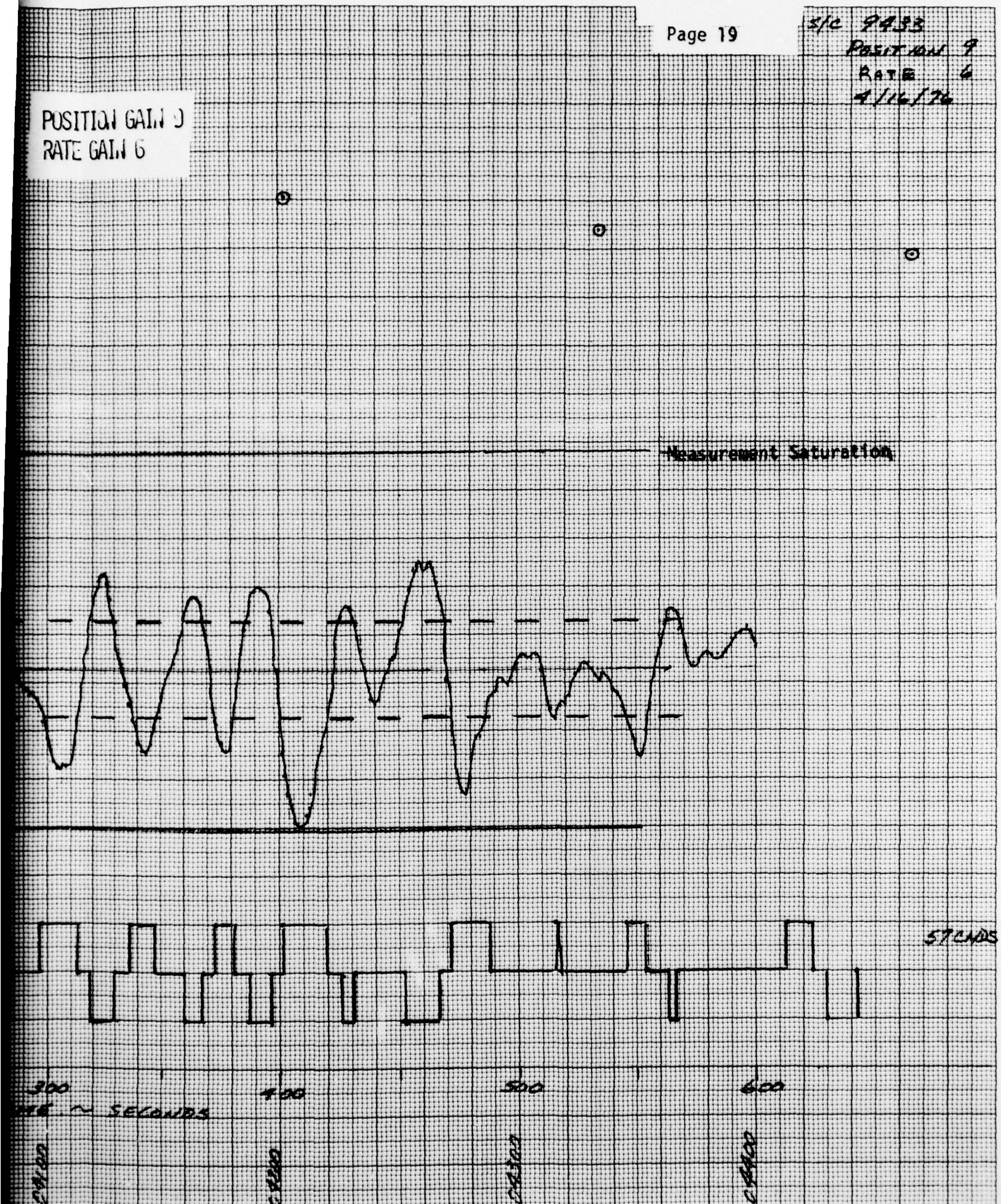


Figure 11. Attitude Error Versus Time for A = 9, C



Versus Time for A = 9, C = 6, 75 RPM (April 16, 1976) was sufficient to control the error even in the case of large disturbances. However, since there were definitely cases where the spacecraft had been knocked off for longer than 60 seconds, it was decided to try the 5 step command block (i.e., ±2 counts), anyway.

It should first be noted that at the nominal position gain of "A" = 6 and with the rate term = 0, it is impossible to get the controller to command more than 1 count. This is because although the first count is sent at ±2.3 deg error with "A" = 6, the second count will not be sent until the error is 6.9 deg, due to the method of command implementation (see Figure 12).

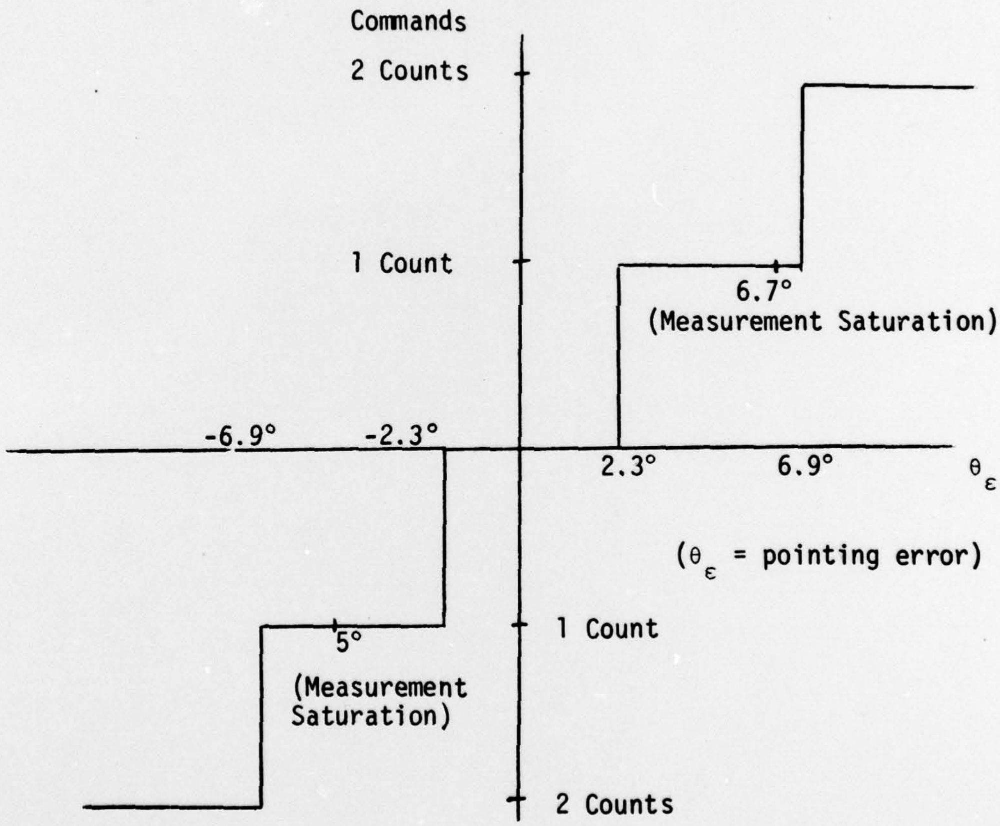


Figure 12. Command Implementation - "A" = 6, "C" = 0

However, the error reading is saturated at something less than 6.9 deg on both sides of the control system. (One side saturates at about 5 deg and the other at about 6.7 deg since there is a bias.)

If a rate term is included with the position term, it is possible to get 2 counts commanded, although with a small rate gain, they will occur infrequently. When a rate term of "C" = 6 was included ("A" = 6 also) the 2 count command was issued only four times in a 2000 sec period. When "C" was increased to 12, there were 3 instances of the 2 count command in a 1000 sec period. These cases were not plotted.

Another way to cause the 2 count command to be issued is to increase the position gain. However, increasing the position gain much above 6 has already been shown to drive the system, rather than control it, and with a 2 count limit in the system is driven even harder. Figure 13 shows this quite clearly where with a gain of "A" = 8 ("C" =0) the error is driven off the earth first on one side and then on the other. (It is interesting to compare this figure with Figure 5, which also had a high position gain of "A" = 8 ("C" =6) but a 1 count command limit. Recall that the Reference indicated that one of the reasons for limiting the counter to 1 count was sort of an "insurance policy" against too high a position gain selection and here this can clearly be seen. In Figure 5 with the counter at ±1, the response is somewhat acceptable but Figure 13 is not.)

5.0 CONCLUSIONS AND RECOMMENDATIONS

The results of the flight tests demonstrates that the ACM system can be used to control the 777 spacecraft with a degree of accuracy sufficient to use the earth coverage antennas. This accuracy is on the order of 2.5 degrees at 75 RPM, and confirms the analysis of the Reference. In addition ACM can recover the satellite from many large transients automatically, and provide more continuous coverage than normal mode under similar high torque conditions. For example during the test period, several attempts were made to put the controller in normal mode, but normal mode could not be held for any appreciable length of time. The longest continuous operation of the ACM controller during the test period was 11 hours and 7 minutes, however. Still, there is no question that when the spacecraft can be operated in the normal mode the performance is better and the narrow coverage antennas can be used. The

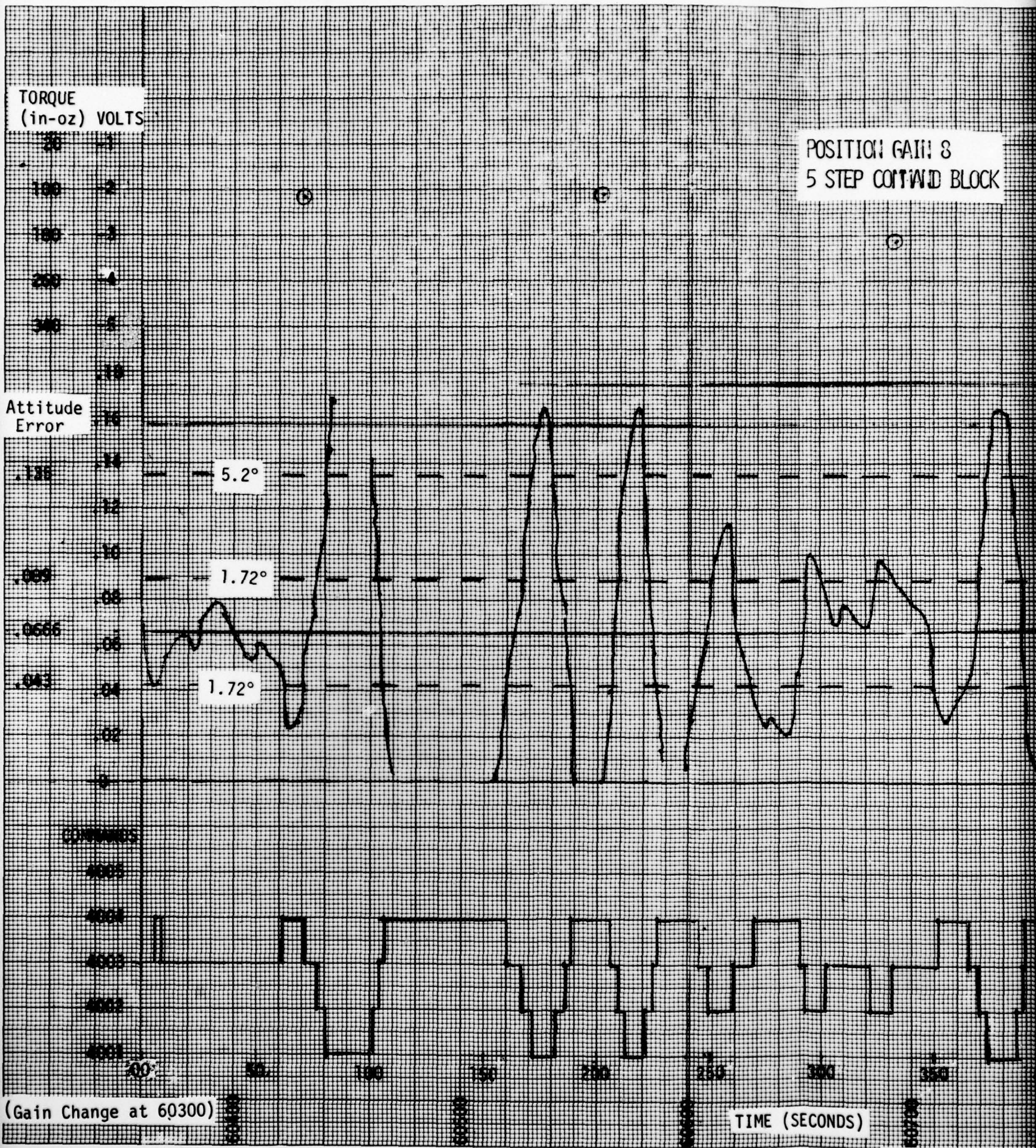
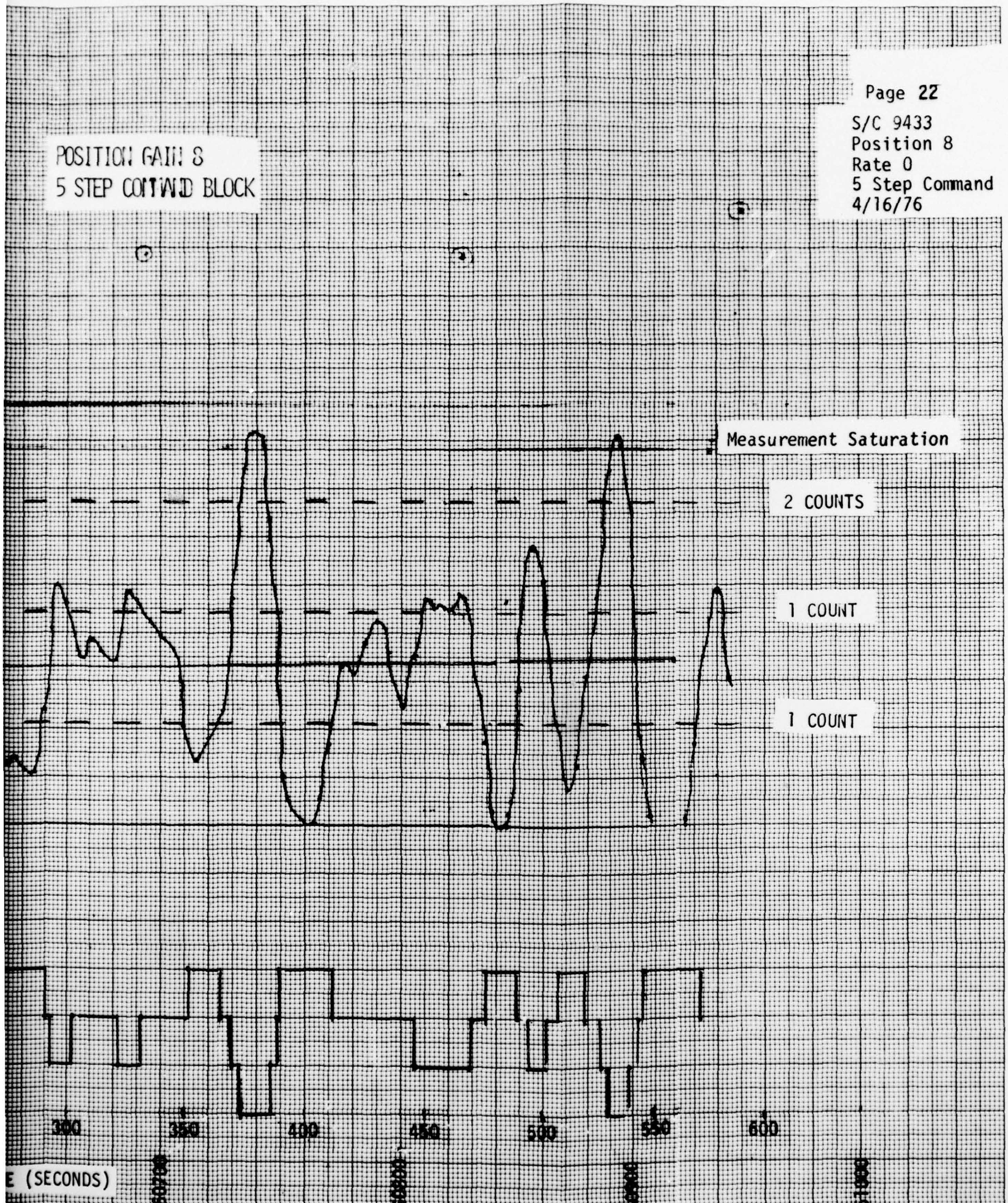


Figure 13. Attitude Error vs Time A = 8, C = 0, 5 Step Command Block (April 16, 1976)



ommand Block (April 16, 1976)

2

general consensus on the overall performance of ACM is that in the presence of large torques, ACM can control the spacecraft for longer periods of time than normal mode, but normal mode is preferable when it can be maintained. Also even ACM cannot control the spacecraft if the disturbances exceed the capability of the motor.

In regards to specific operation of the spacecraft at 75 RPM, it is recommended that a position gain of "A" = 6 and "C" = 8 be utilized, along with the 3 step command block (±1 count limits). Not much chance for testing the 60 sec limit for time off the earth was given in the test period, but since the system was seen to reduce transients that had been off as long as 40 sec, it should definitely not be reduced. An increase in the time limit should not have any adverse affects, and should be tried in order to give the system time to recover from the larger transients. If it is desired to vary the position and rate gains, the variations should be restricted to values of "A" = 6 or 7, and "C" = 0 through 8.

During the testing period, a reduction in spin speed was not authorized. However, analytical results predict better performance at lower RPM because higher position gains can be tolerated. Since excellent agreement was obtained between the simulation and flight data at 75 RPM, it is reasonable to expect that better performance would result at the lower RPM. Since the test results show that the rate gain selected in the reference was somewhat high from a command rate point of view, it is recommended that if the tests are made at lower RPM's, that they be made with a position gain <u>only</u> at first, and that the "C" value from the reference not be used. (This is because the "C" value from the reference did not consider the rapid small friction fluctuations, and these result in an unnecessarily high command rate if the "C" term provided in the reference is left in.)

The table below gives the recommended position gains and gain states from the Reference at 40 and 60 RPM, as well as the conclusions of the flight tests conducted at 75 RPM.

RPM	G.S.	A (Bias Counts/ Telemetry Counts	Deg Error When 1 Count Sent
40	6	.010 (10)	.75
60	8	.0075 (7 or 8)	1.5
75	8	.006 (6 or 7) .007	2.3 (6) 2.0 (7)

It should also be noted that there is more margin in the position gains selected at the lower RPM. That is, the possibility exists that the position gain could be increased over the recommended value. (This fact was not explicitly stated in the Reference.)

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