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TESTS OF A POSITION ACTUATOR FOR THE TEN METER TELESCOPE SEGMENTS

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TABLE OF CONTENTS

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SUMMARY

A microprocessor controller for the TMT actuator has been built and tested. An 8 bit MOS 6502 and an early model of the roller-screw actuator were used. Performance has been achieved that could meet the probable speed and precision requirements of the TMT. Significant improvements are expected when the new integral bearing actuators are available.

An important goal of this work has been to keep the electronic circuitry simple, with a small number of well proven components. No special set-up adjustments are required, and maintenance by blind parts replacement should be straightforward.

INTRODUCTION

Possibly the most critical element of the Ten Meter Telescope structure will be the "actuators" which are required to align the 36 segments of the primary mirror. There will be many critical electronic elements of the TMT; the actuators, because they are state-of-the-art electro-mechanical devices, are more likely to cause long-term problems. The actuators must produce linear motions precise to a few nanometers over a range of more than 10^3 microns. There are numerous anecdotes that say this cannot be done; problems with dirt, lubrication, stiction etc., are mentioned. Since our telescope depends on the motion being done reliably and precisely over many years by over 100 individual actuators, an independent evaluation of possible problems seemed important.

The work and test results reported here have been directed partly towards detecting peculiarities of the roller-screw actuator and partly towards the development of a simple microprocessor-based electronic system that can control the movement of the actuator with the speed and precision needed for the TMT. Some modest success in controlling an early version of the actuator is reported here. It is expected that the control algorithm will perform much better with the lower friction devices now being assembled by George Gabor.

A roller-screw actuator was built in the Lick shops, and a microprocessor-based circuit was designed to control its motion. The roller-screw, torque motor and encoder are those used by Gabor, and the mechanical design is similar to the one used by Gabor. The electronic controller uses an MOS 6502 8 bit microprocessor with peripheral circuits that have been field tested by many users for several years.

A block diagram of the controller hardware is shown in Figure 1. A large fraction of the hardware is needed for testing but would not be used in an actual operating situation. The most critical part of course is the software and a flow diagram for the central control algorithm is shown in Figure 2. There are a number of useful features such as self-checking of hardware and diagnostic routines that will not be described in this brief report.

THEORY OF OPERATION

The BEI incremental encoder produces dual sine waves, approximately in quadrature, 2048 complete cycles per revolution. The pitch of the roller screw is 1mm (1000 microns) per turn. Thus one sine wave from the encoder translates to a linear distance of 488 nm. The sine waves feed an 8 bit analog-to-digital converter (ADC). Using arc-sine look-up tables to convert the ADC readings, the two quadrature sine waves allow interpolation to 1.9 nanometers. (For convenience, this least significant interval is rounded to 2 nm throughout this report.)

The amplitudes of the sine waves are both temperature and power supply dependent and the phase angle between the two is not exactly 90°. To correct for these imperfections, the microprocessor continually monitors the peak level of each sine wave and generates new arc-sine look-up tables whenever a significant variation in amplitude is detected. The deviation from exact quadrature is also measured and used as a correction to the position interpolation.

The "sine-waves" are not true sine waves, so that the arc-sine interpolation is not precise. A first order correction is obtained by mixing the readings from both curves in the region where the "shoulders" of the curves occur.

The absolute error from the arc-sine encoder translation should be only a few percent of a 244 nm half cycle. (This is only an estimate, since absolute measurements of this precision cannot be made with our existing instrumentation.) However, any encoder translation error will be a smooth function. The mirror control system will be a closed loop, with updated position-feedback 10 or more times per second. The motion required due to telescope support flexure is expected to be less than 100 nm per second. Thus, the motion increments at each updating should only be a few nanometers, and errors of a few percent of the requested motion will be unimportant. Larger correction motions will be required to overcome wind loading, but here again, an error of a few percent in the position correction will not be serious.

The approach outlined above allows the roller-screw rotational position to be measured with a precision equivalent to 2 nm of linear position. The accuracy, although not of as great importance in a feed-back system, should be within 20 or 30 nm. The microprocessor also controls the motor current, and can change the duty cycle of the driving voltage in about 200 μsec. A complete cycle of reading the position, computing the error from desired position, and updating the motor current, requires about 1 msec. Thus, in principle, a fairly high bandpass control system is possible.

SOME RESULTS

The most severe limitation on the frequency response of the system is a mechanical resonance with a period of 7 or 8 msec. This resonance has been seen sometimes even with the feedback loop open. George Gabor believes that the pulse-width modulated motor-drive excites the resonance, and in fact, since the drive pulse period was reduced from 128 μsec to 64 μsec, the resonance has only been seen when running with a closed loop. However, the resonance is very easily excited, and is usually seen at amplitudes of perhaps ± 15 nm equivalent on the encoder output, when moving the actuator. Various combinations of velocity and acceleration feedback help a little. Reducing the loop gain reduces the oscillation amplitude, but also reduces the setting precision. There also may be some frequency response limitation caused by the flexibility of the coupling of the encoder to the screw. The effect of this is not known.

Stiction is a major problem for small mechanical motions such as those needed on the actuator. As the motor torque is increased, little or no motion is seen; then suddenly the screw starts to slip, and before the drive current can be adequately adjusted, greater than desired travel occurs. If the feedback gain is increased enough to stop all stiction-caused problems, oscillations result. The presence of stiction together with mechanical limitations on the control bandwidth means that no simple linear control system will work well, because the response characteristics of the system vary over a wide range.

One of the goals of our tests was to find a computer algorithm that would have enough "intelligence" to get around the non-uniform behavior due to stiction. This goal has only been partially met. At low continuous speeds (about 1 micron per second or less), the motion produced is quite smooth, and the rms error from the desired position is only a few nanometers. The maximum errors seen are less than 60 nm. In "good" sections of the screw, the maximum errors are less than 20 nm. However, for higher continuous velocity, the average and maximum position errors become much worse. The algorithm now used is a compromise that reduces stiction-produced errors without causing large oscillations.

The actuator controller has a large dynamic range of controlled motion from 500 microns per second down to single 2 nm steps at any interval greater than 2 msec. (Precise steps of up to 1 micron in 200 msec are also possible, but there is serious concern that such stepped motion could excite unwanted mechanical oscillations in the telescope, so that such "high-speed" motion will probably be avoided.)

SOME FEATURES OF THE PROGRAM

A number of tests of the actuator performance can be made. By keying in various constants, and by the use of a selector switch, various modes of operation are possible. Cumulative tabulations of position and velocity errors as well as diagnostic snapshots showing motor drive duty cycle, position errors, acceleration and velocity, are recorded for these tests and are displayed on a video monitor. Tests available include the following (labeled by switch position):

5 - Move from limit to limit at full speed, then move to a pre-selected central position.

6 - Move and stop continuously.

7 - Move rapidly from one location to the other, delay, move back rapidly, then repeat.

8 - Measure the deviation from quadrature of the two sine waves at 4 points in the cycle.

9 - Move continually in a switch-selected direction at a key pad selected low speed.

10 - Move in repeated rapid steps of a selectable size and with a selectable delay between steps.

11 - Move back and forth in a non-symmetrical sawtooth pattern, producing a continuous additional motion in one direction. Direction reversals of 2 to 20 per second can be used. This pattern approximates the motion that might be required to control the mirrors while the telescope is tracking with wind buffeting.

SOME TYPICAL OPERATION RECORDS

Although the rotary motion of the roller-screw can be controlled and its performance measured, it must be shown that the linear motion is accurately represented by the rotary motion. A MAHR sensitive position detector was used to actually record the linear motion of the actuator, running at different rates. In the tests shown in Figure 3, a sawtooth motion was requested of the actuator. The sawtooth was non-symmetrical, so that some tracking motion occurred as well as the sawtooth motion. The incremental-encoder reading was recorded and compared with a "demand" position, and the motor drive-current adjusted, every 1.3 msec. The instantaneous velocity, position, motor drive and position error also were recorded, and an error distribution table updated every 1.3 msec.

The tracings of Figure 3 show that the actuator does produce well-controlled linear motion. However, the linear motion was not calibrated in the test. The peak-to-peak motions listed are what the rotary motion would produce if there were an exact conversion of rotary to linear motion. In fact, when the direction of motion reverses, the linear motion starts out at only about one-half what one would expect from the encoder readings. After about a micron of motion in one direction a full translation rate is reached. This is presumably due to squeezing of lubricant out of the roller-screw. Hopefully, the conversion of rotary to linear motion will be more precise when dry dicronite lubrication is used as is being done for the actuators used in the TMT Technical Demonstration.

In any case, the frequency response of the actuator and controller can be estimated from the tracings. As should be obvious, the frequency response and setting precision obtainable are functions of the amplitude of the motion required.

In Table 1, a typical diagnostic record is shown.

Position error distributions obtained for various speeds of uniform and sawtooth motions are plotted on the sheets following Figure 3. Note that these are log plots. Error distributions are shown for sawtooth motions of 40, 90, and 180 nm, where the repetition rate was 4.5 complete cycles per second. The rms errors are 6, 9, and 12 nanometers for the three cases. The error for 99% of all cases is less that 20, 30, and 45 nanometers respectively. Error distributions are also shown for sawtooth motions of 30 and 60 nm with a period of 100 m sec. Here the rms errors are 9 and 15 nm with 99% of all cases showing errors less than 25 and 50 nanometers. Error distributions are also shown for the actuator tracking smoothly at rates of 90 nm/sec and 1500 nm/sec.

It is noteworthy that the error distributions are quite non-symmetrical for the faster motions, with the largest errors occurring when the screw is pushing against the load (roughly 100 lbs. for these tests). When the

TABLE 1

Typical Diagnostic Record

Velocity	Acceleration	Position	Position Error	Updated Drive Duty Cycle
1	0	327631	7	203
-1	-2	30	5	208
0	1	30	4	204
0	0	30	3	205
1	1	31	3	200
-1	-2	30	1	206
0	1	30	0	206
0	0	30	-1	210
1	1	31	-1	207
0	-1	31	-2	217
1	1	32	-2	215
1	0	33	-2	217
0	-1	33	-3	227
1	1	34	-3	226
1	0	35	-3	229
3	2	38	-1	224
2	-1	40	0	224
3	1	43	+2	219
4	1	47	5	209
5	1	52	9	199
4	-1	56	12	189
3	-1	59	14	179
-2	-5	57	11	184
-2	0	55	8	188
-1	1	54	6	186
2	3	56	7	176
2	0	58	8	166
-2	-4	56	5	171
-4	-2	52	0	176
0	4	52	-1	166
3	3	55	1	161

The data shown above were taken with a continuous tracking rate of 1.5 microns per second. It is typical of the performance obtained at that speed, and covers a time interval of about 40 msec. The units of distance are 2 nanometers. The control algorithm increases the drive duty cycle for positive position errors and also for positive velocity and acceleration.

This segment of data was selected because it includes an excursion caused by the stickiness of the bearing.

encoder output is observed with an oscilloscope, the motion is noticeably rougher in the loaded direction, presumably because the sticking behavior of the screw is worse in that direction. Measurements made with a load of 300 lbs. on the actuator give very similar results.

These results are typical of those seen at most positions on the roller-screw. At a few locations on the screw the motion becomes very smooth. The error distributions shown here were taken over what appeared to be an average area of the screw, and included one section that seemed as bad as any.

CONCLUSIONS

The results obtained here suggest that control of the actuators for the TMT should be straightforward. Simple-minded hardware and software seems adequate to give precise control for rates of motion less than 1 micron per second. Maintenance of this type of digital hardware is an easy matter of module replacement, with no special adjustments required.

The stickiness of the actuator bearings seems to be the main limitation on performance. New integral-bearing actuators now being assembled by George Gabor are expected to be much smoother in operation.

Long term tests of several actuators will have to be done in order to get some idea of the margins of reliable operation. Until then, tests such as this one can only be regarded as an additional indication that control of the segmented mirror will be feasible.

ACKNOWLEDGEMENTS

This work was suggested by Jerry Nelson. Numerous conversations with George Gabor have been very helpful.

Jack Osborne and Eric Horn have assisted in setting up mechanical tests and by making adjustments of the actuator hardware. The micro-computer cards and assembly were designed by Terry Ricketts.

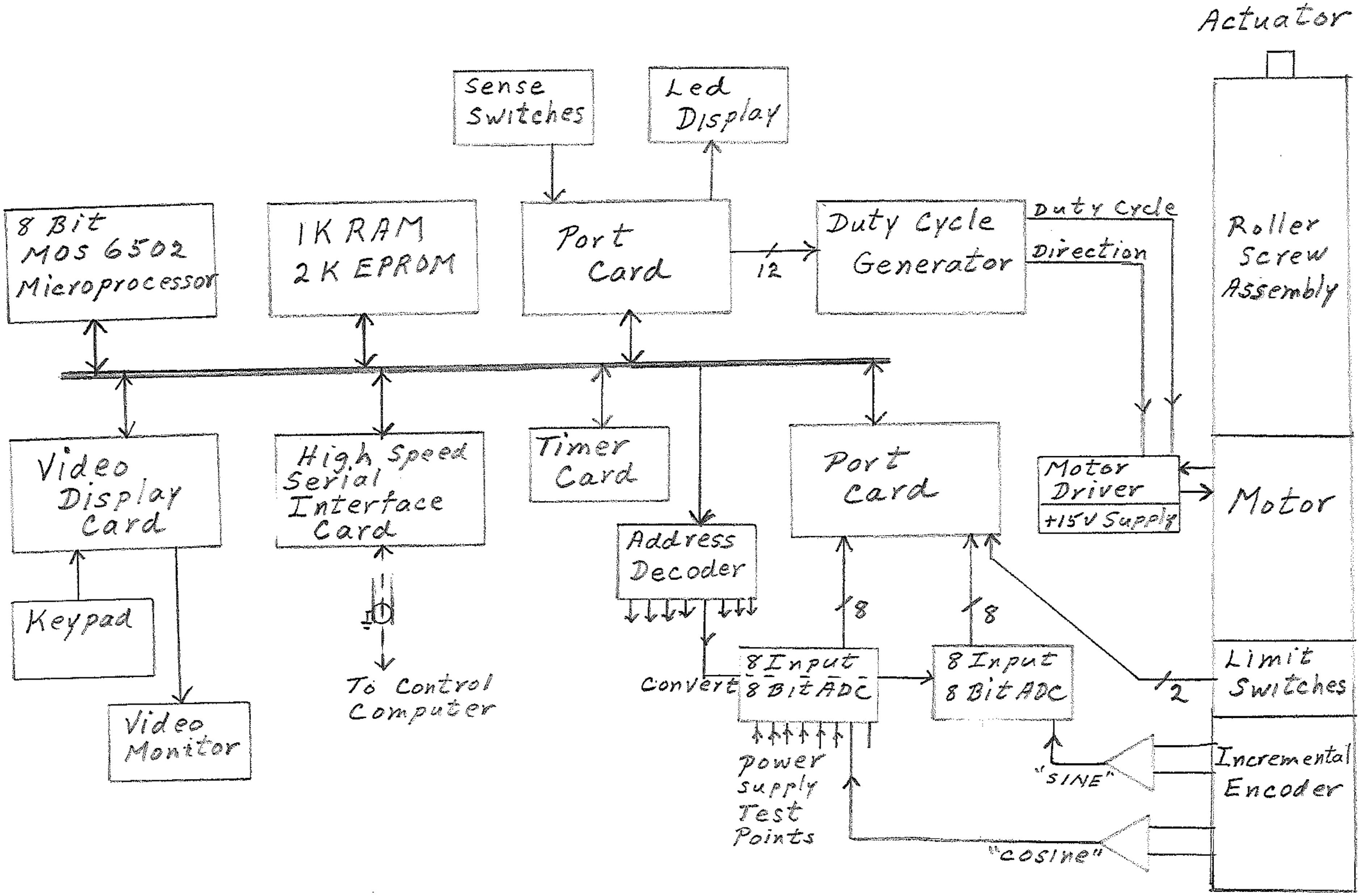


Fig. 1

Actuator Control Electronics

Actuator Control June /82

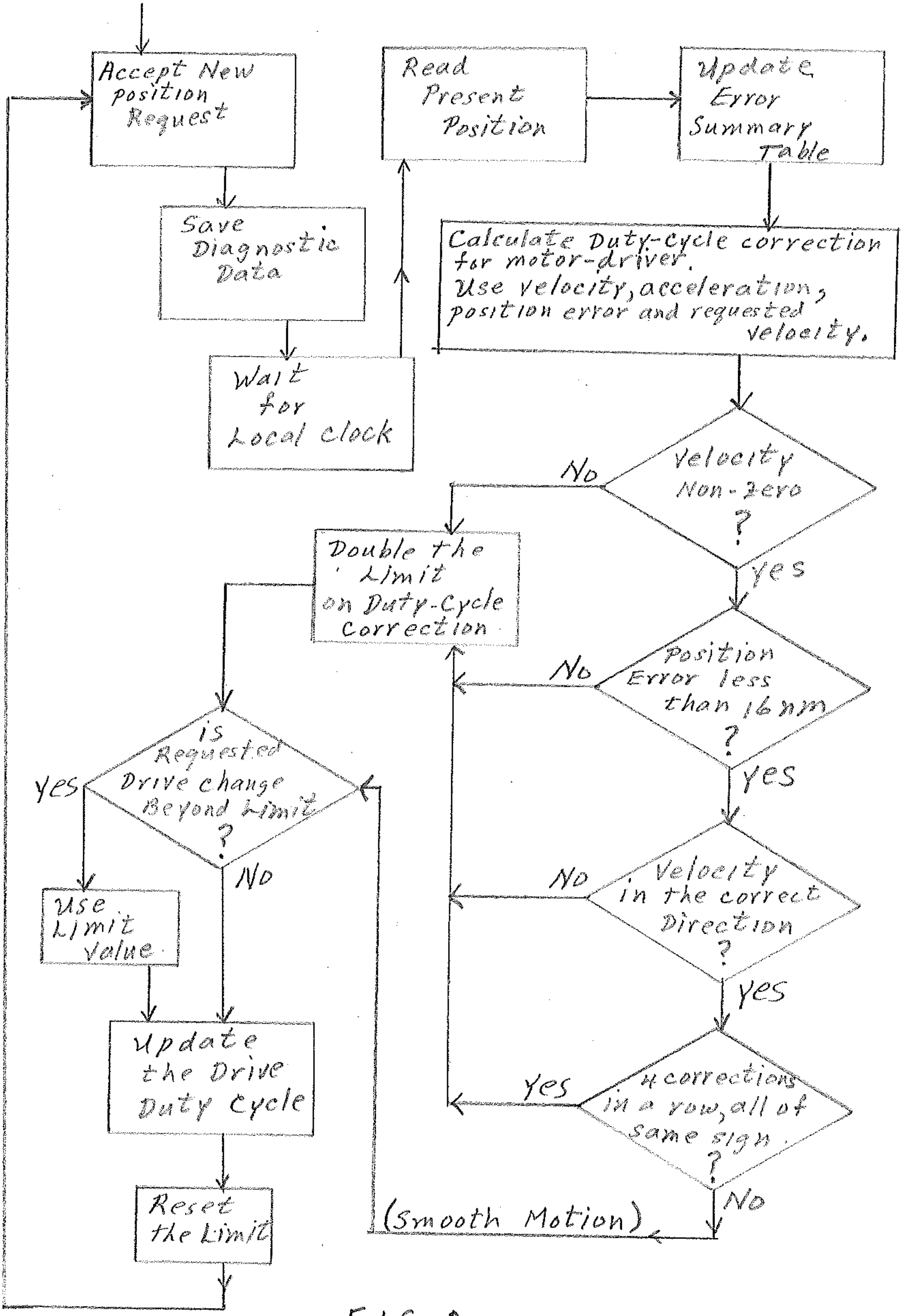
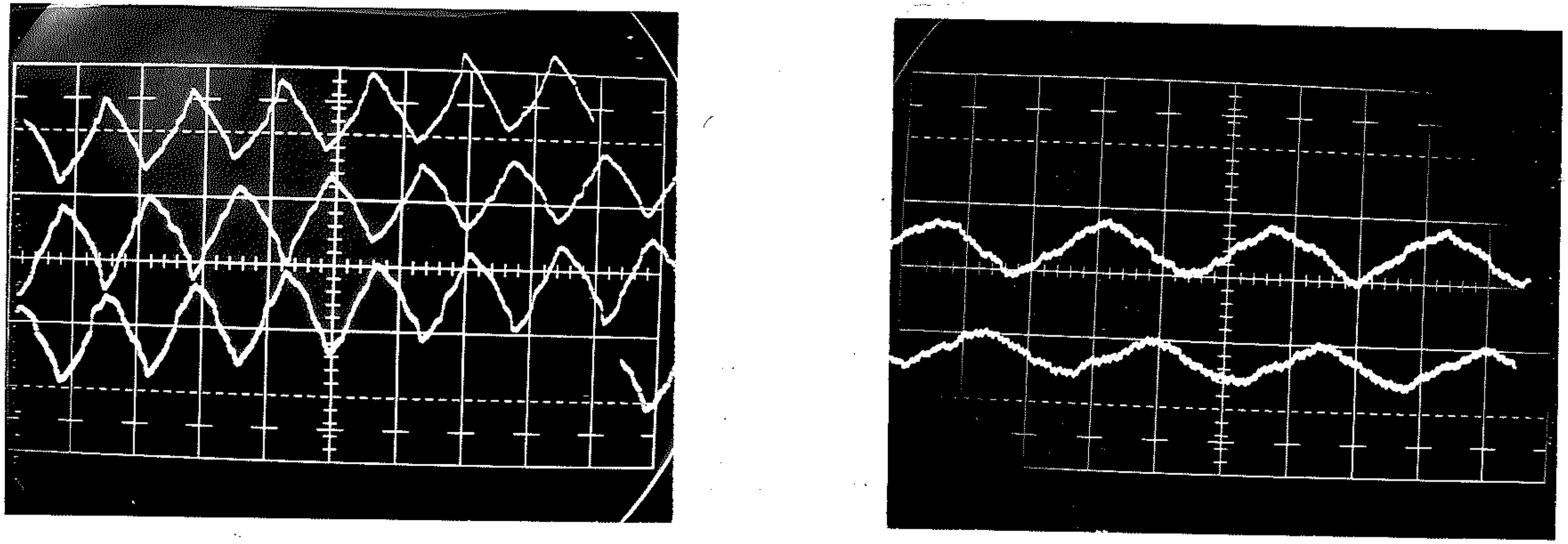
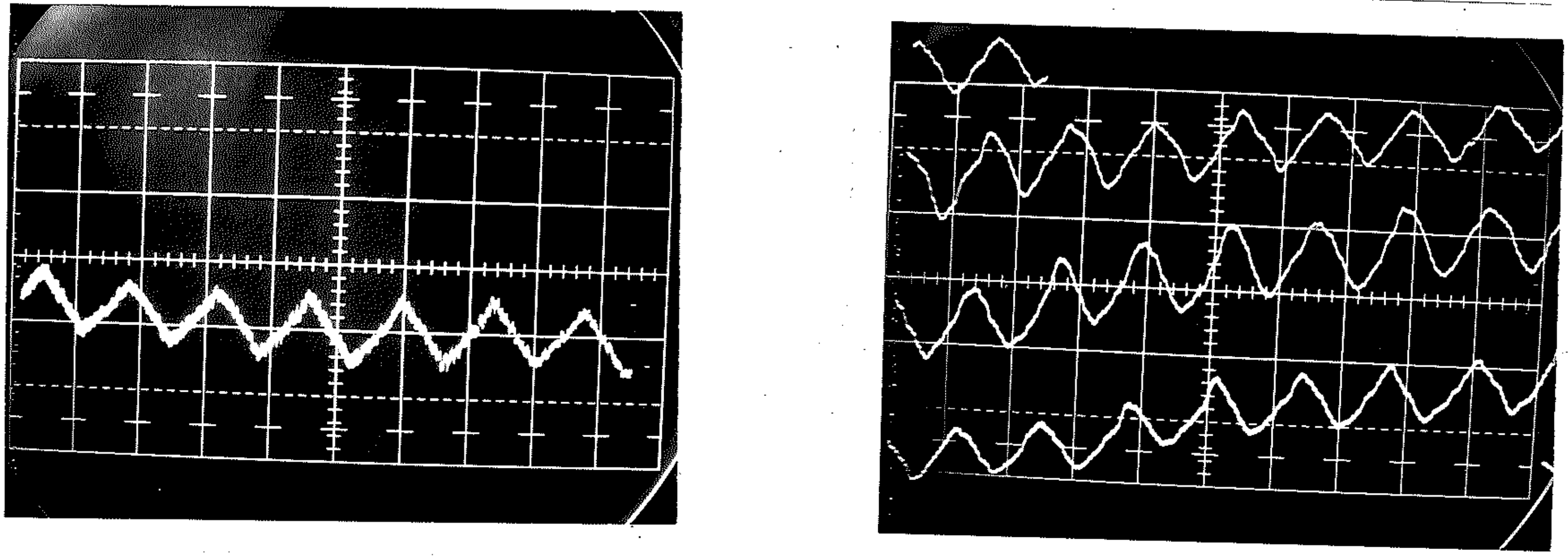


FIG. 2



0.5 sec/cm
128 nm sawtooth a

0.1 sec/cm
48 nm sawtooth b

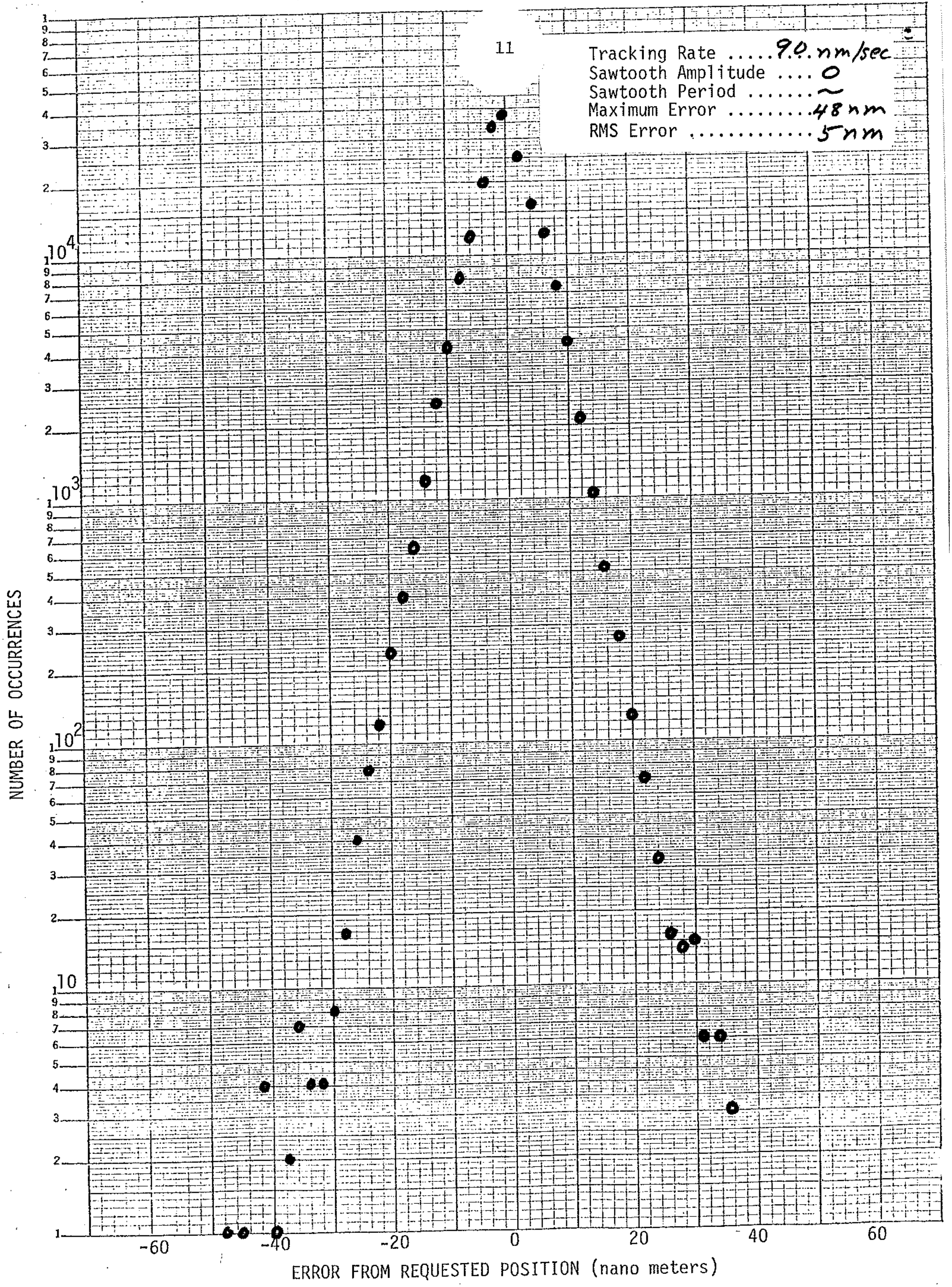


1.0 sec/cm
64 nm sawtooth c

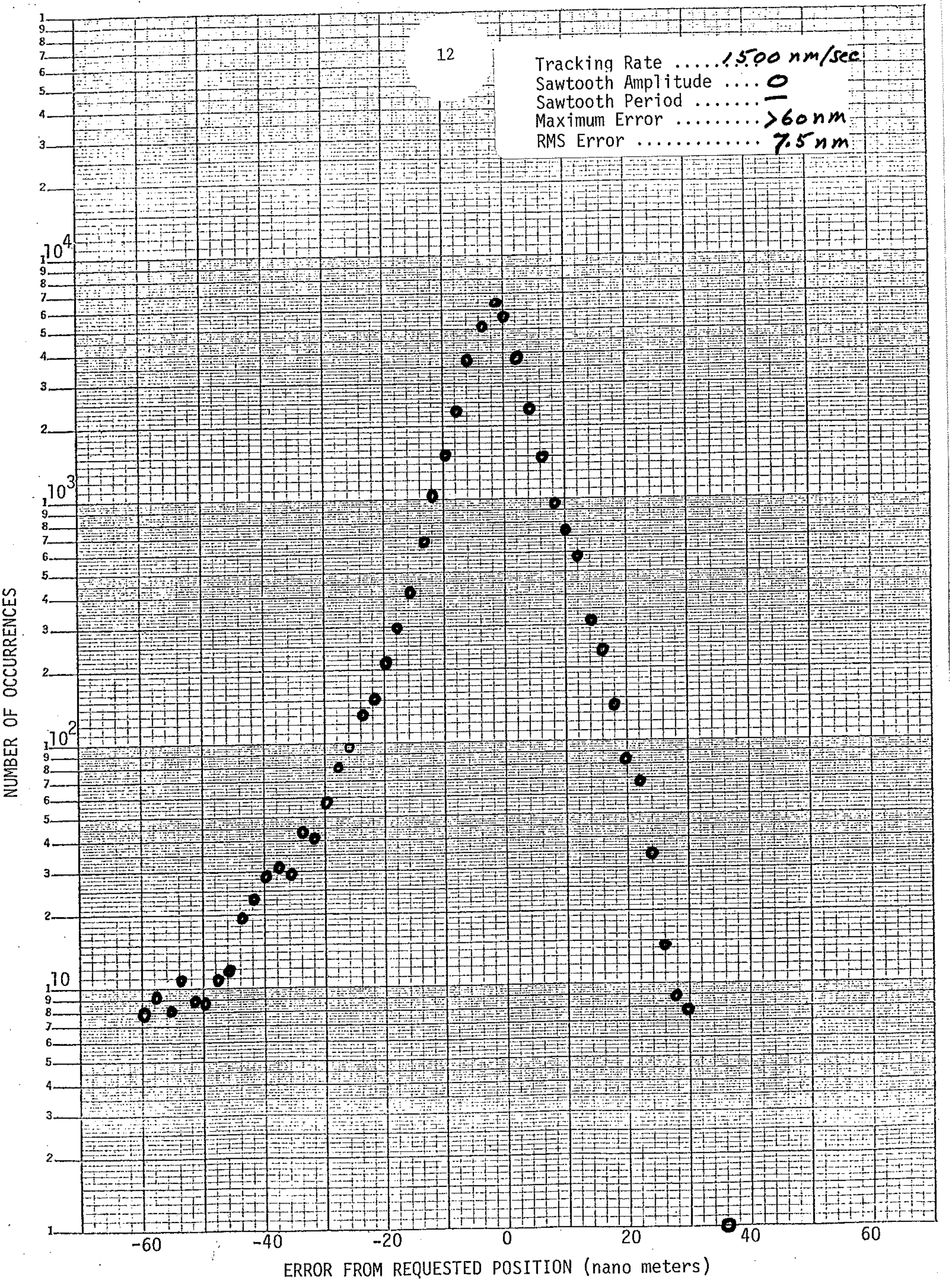
0.1 sec/cm
96 nm sawtooth d

ACTUATOR TEST RECORDS

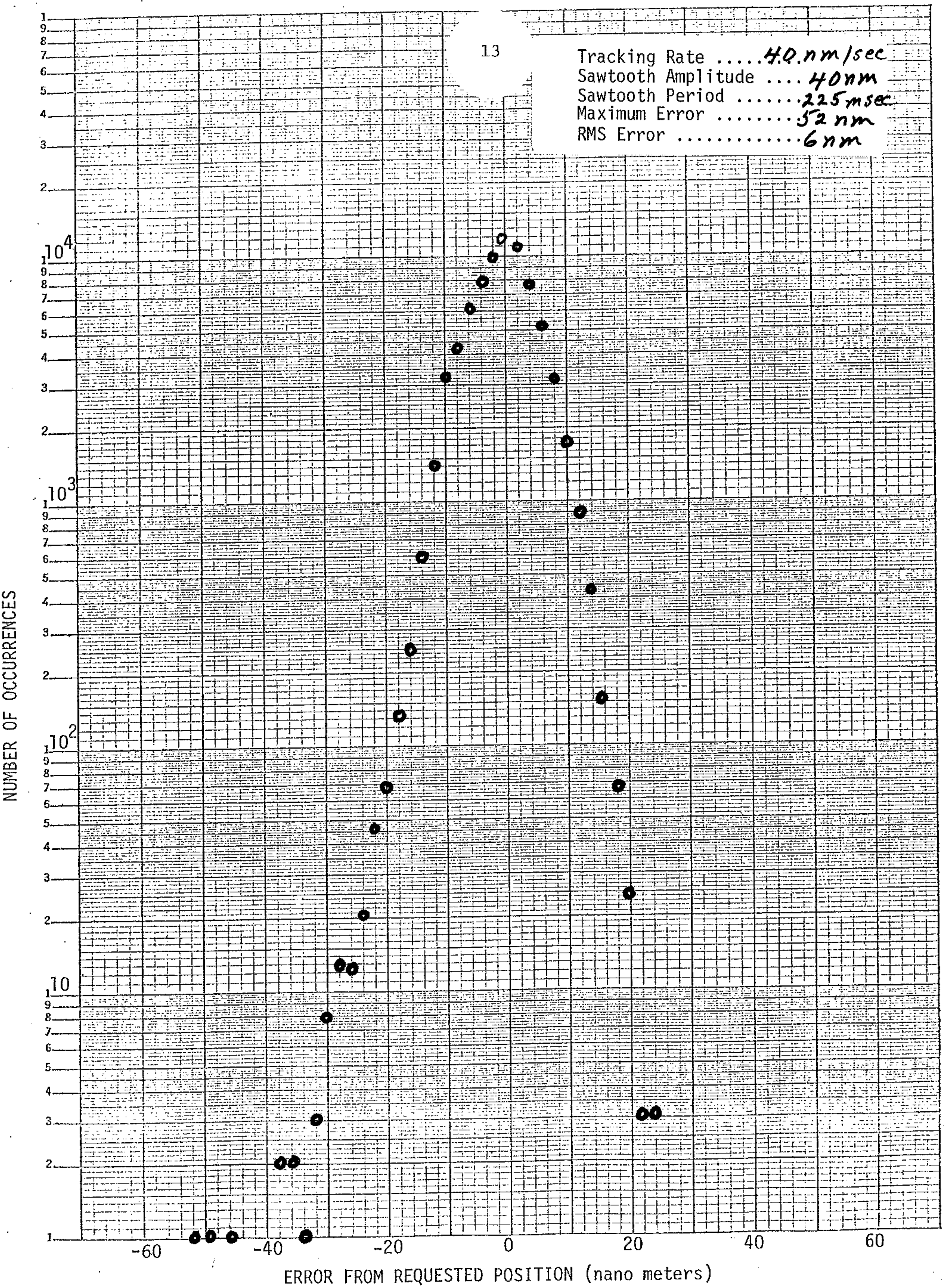
FIGURE 3



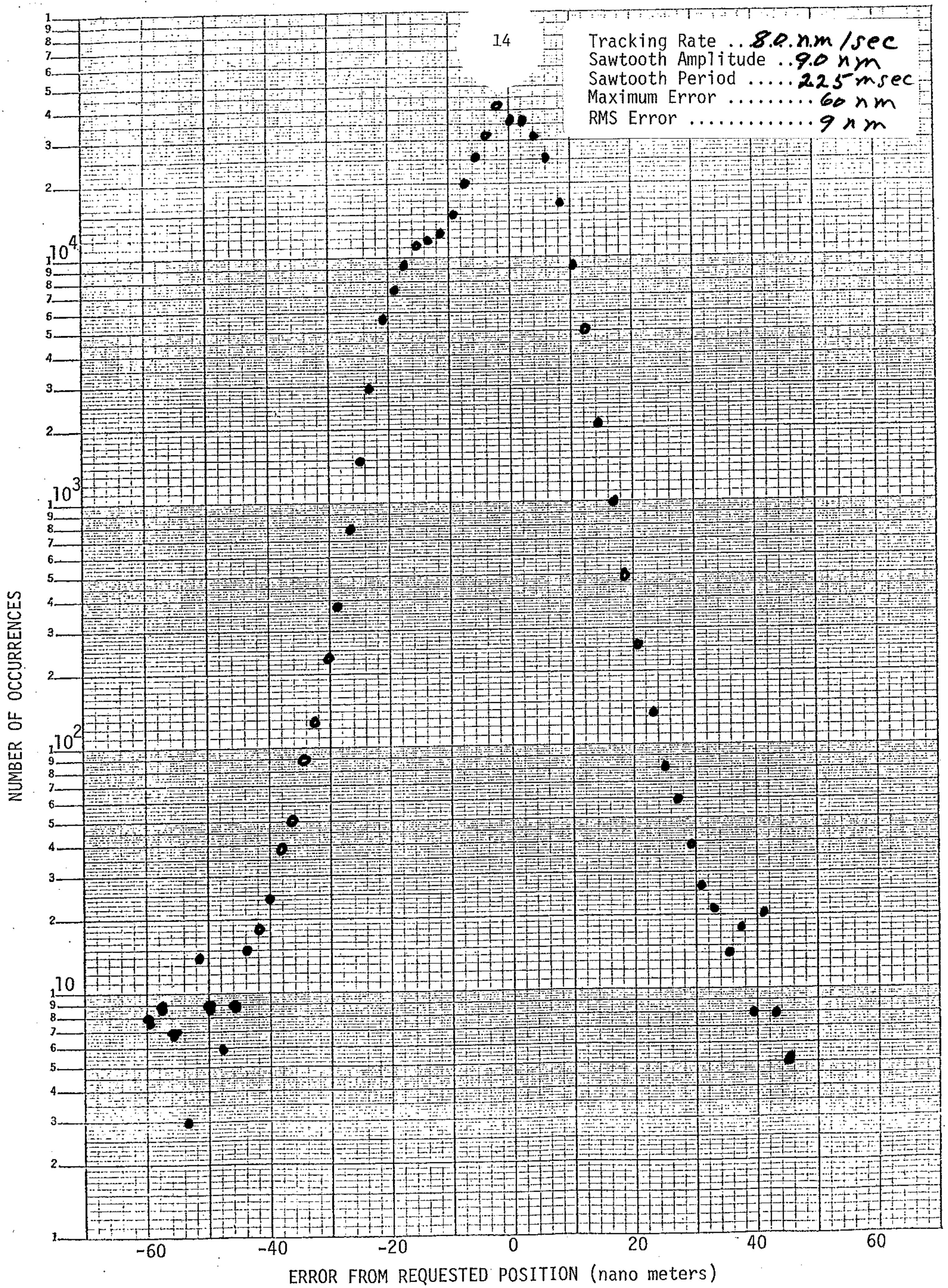
Tracking Rate ..... 9.0 nm/sec
Sawtooth Amplitude 0
Sawtooth Period .... ~
Maximum Error .... 48 nm
RMS Error .... 5 nm

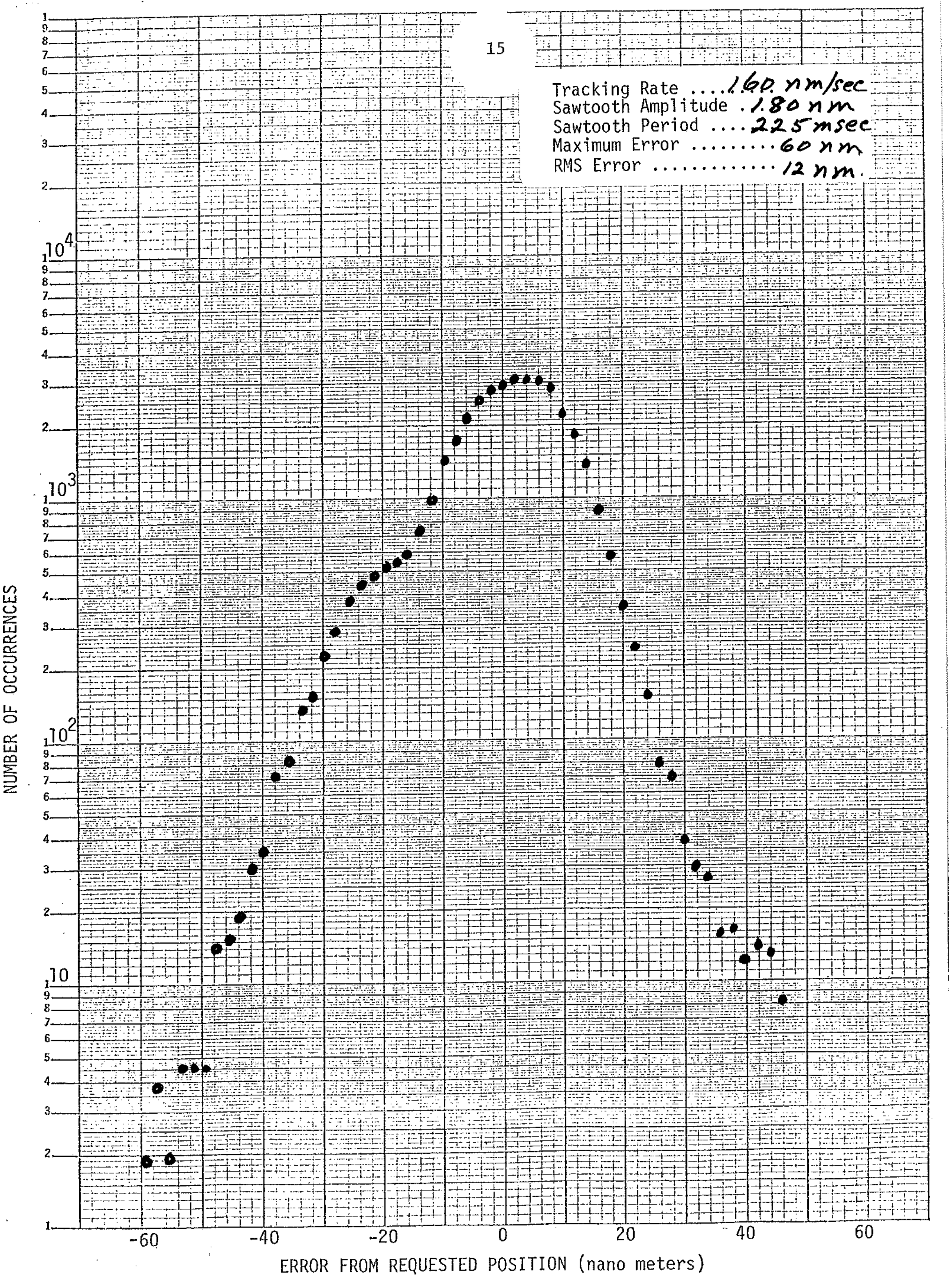


Tracking Rate ..... 1500 nm/sec
Sawtooth Amplitude 0
Sawtooth Period .... —
Maximum Error .... >60 nm
RMS Error .... 7.5 nm

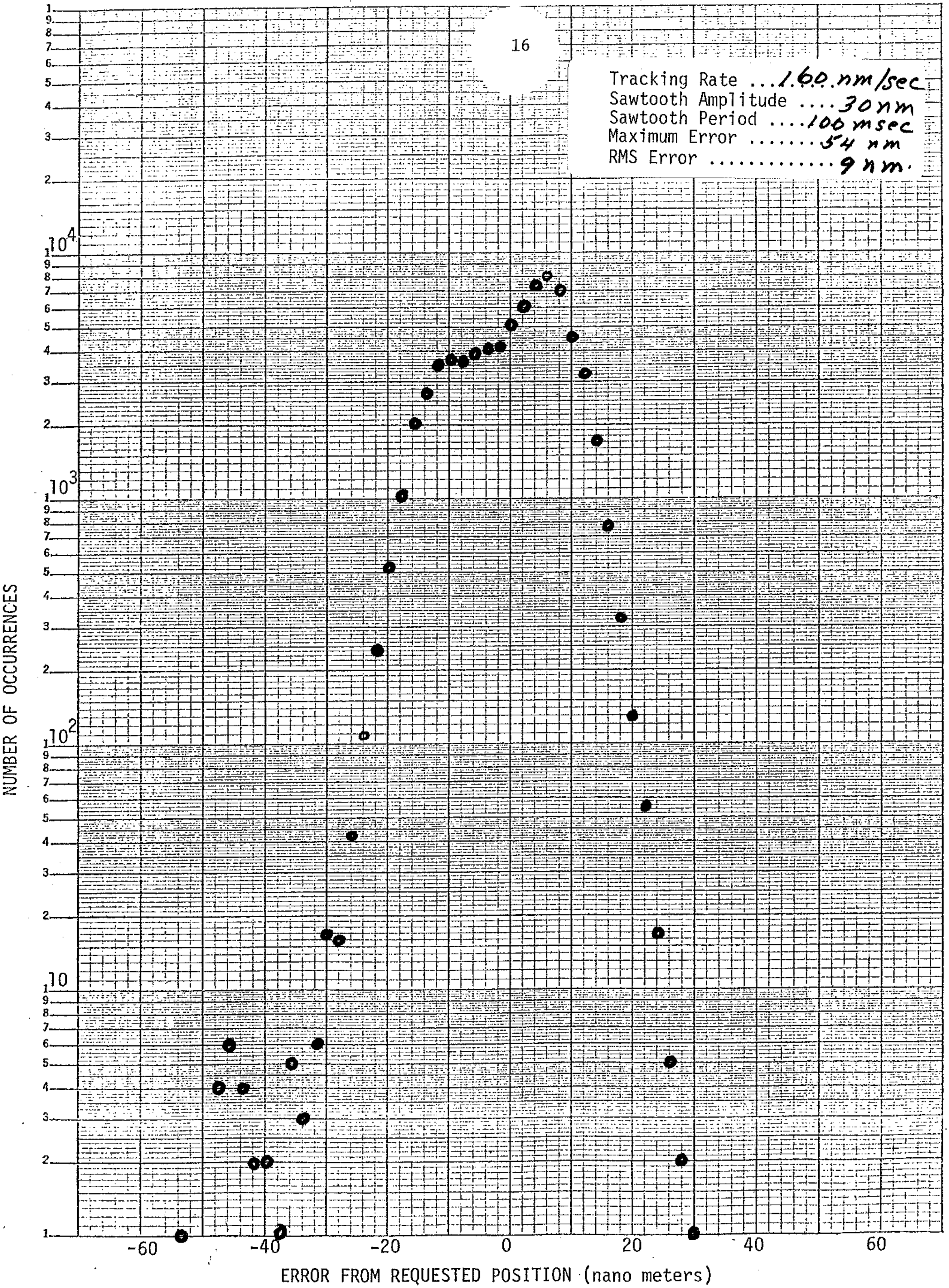


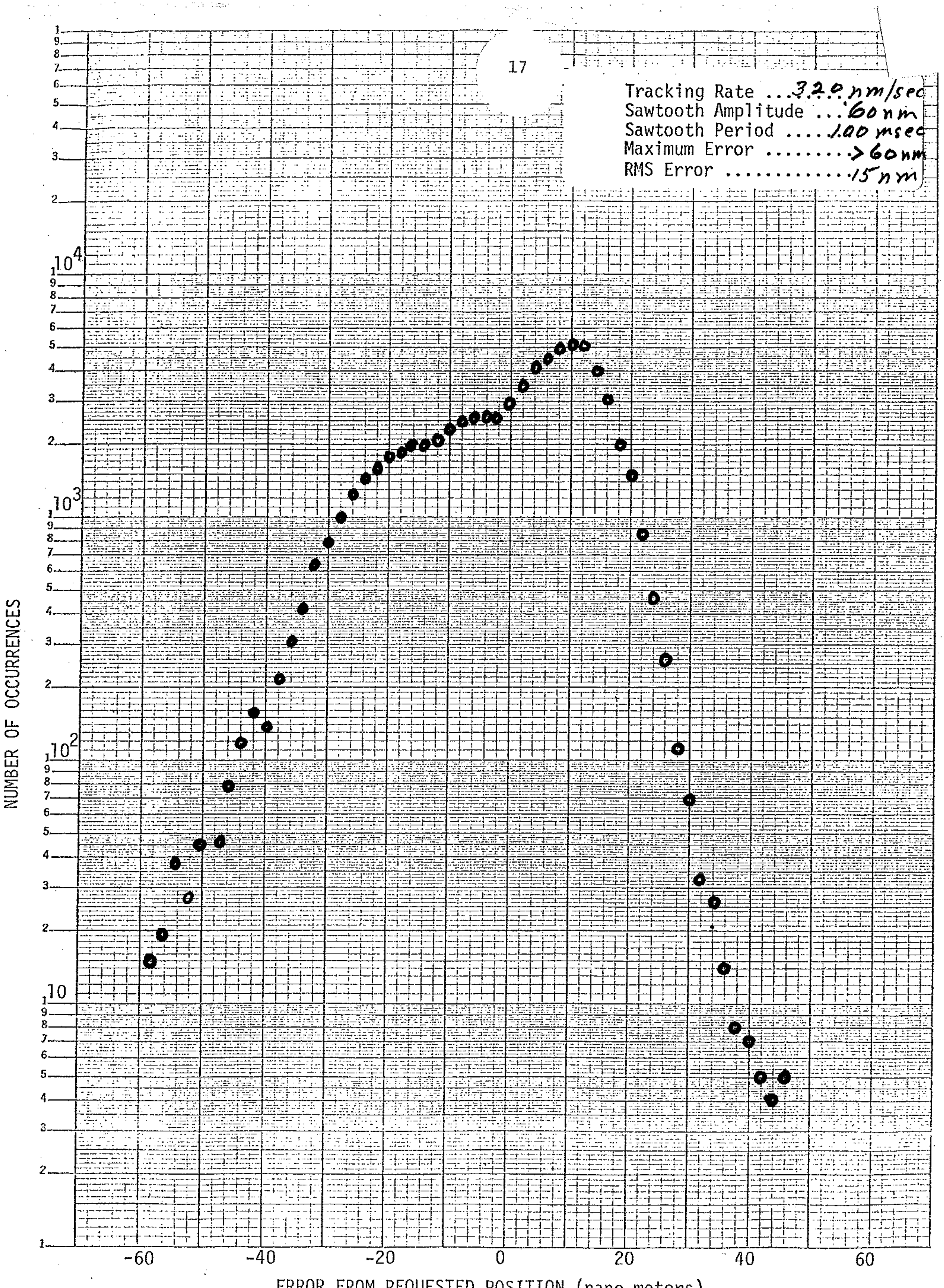
Tracking Rate ..... 4.0 nm/sec
Sawtooth Amplitude 40nm
Sawtooth Period 225msec
Maximum Error .... 52 nm
RMS Error 6nm


Tracking Rate .. 8.0 nm/sec
Sawtooth Amplitude .. 9.0 nm
Sawtooth Period ..... 225 msec
Maximum Error .... 60 nm
RMS Error .... 9 nm
NUMBER OF OCCURRENCES
10^4
10^3
10^2
10
1
2
3
4
5
6
7
8
9
-60
-40
-20
0
20
40
60
ERROR FROM REQUESTED POSITION (nano meters)



Tracking Rate .... 160 nm/sec
Sawtooth Amplitude . 180 nm
Sawtooth Period .... 225 msec
Maximum Error .... 60 nm
RMS Error .... 12 nm.


Tracking Rate ...1.60 nm/sec
Sawtooth Amplitude ....30 nm
Sawtooth Period ....100 msec
Maximum Error ....54 nm
RMS Error ....9 nm.
NUMBER OF OCCURRENCES
10^4
10^3
10^2
10
1
2
3
4
5
6
7
8
9
-60
-40
-20
0
20
40
60
ERROR FROM REQUESTED POSITION (nano meters)



Tracking Rate ...3.2.0 nm/sec
Sawtooth Amplitude ...60 nm
Sawtooth Period ....1.00 msec
Maximum Error ....>60 nm
RMS Error ....15 nm