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1985 Vertical Survey of the AGS

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Accelerator Division
Technical Note

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I. INTRODUCTION

The elevations of the magnets in the AGS are determined by the standard surveying techniques for determining elevations, which are probably centuries old. However, we do require extreme precision and over time we have fallen into the practice of applying analysis techniques which are inappropriate to the statistical nature of the data. This note reviews our survey system, points out the analysis and procedural errors we are making, and suggest a program for improving our procedures. In general of course, the AGS works well enough so that a large investment in surveying is rarely called for. However, we hope to establish a solid procedure and develop a well understood vertical alignment for the AGS.

II. VERTICAL SURVEY TECHNIQUE

Around the ring there is a set of 38 fixed targets mounted on the tunnel wall. We choose one of these as our starting point, assign it an arbitrary elevation, E_1, and then, using a surveyor's level measure the difference in elevation between the first and the second targets, e(1,2). We then measure the difference between the second and the third, e(2,3), and so on. Relative to the first target the elevation of the other targets is found by summing these differences. The magnet elevations are then found by measuring their elevations relative to a nearby target. However we are going in a closed circle around the AGS, so that when we come back to the first target the total sum of the differences should be zero, which it never is. There are three sources for this problem:

1. Errors, by which we mean the natural random error in the precision of the measurement. We assume these errors have a Gaussian distribution with a standard deviation of d, where d is about 0.003 inches.

2. Blunders, by which we mean such things as misreading or misentering a number. Blunders are frequently of the form 1.000 inches (easily detected), and perhaps sometimes of the form 0.010 inches (very hard to distingquish from errors.)

3. Target movement. Targets may move because a human moves them, the ground moves (unloading some roof beams can produce a 0.040 inch effect in a few hours), or perhaps through their own perversity.

The survey group must now undertake what is essentially an impossible task. It must eliminate blunders and target movements from the data. Over the short term target movement is fairly easy and large blunders can be found, but small blunders are indestinguishable from errors, and it is this process of cleaning up the data that eventually leads to trouble, as any particle physicist can attest. However, after a certain amount of resurveying and rechecking we have what we assume is a good set of data, 38 measurements e(i,i+1) each with a measurement error d. Then the uncorrected elevation of target m is given by:

$$E'_m = E_1 + \sum_{i=1}^{m-1} e(i,i+1)$$

Where E_1 is the arbitrarily assigned elevation of the initial target. For the thirty ninth target which is of course the initial target the formula gives:

$$E'_{39} = E_1 + \sum_{i=1}^{38} e(i,i+1)$$

We call the closing error

$$E'_{39} - E_1 = \sum_{i=1}^{38} e(i,i+1)$$

Statistical theory, in particular random walk analysis, tells us that for a large number of measurements of the ring the mean value of the closing errors is zero and they have a Gaussian distribution about zero with a standard deviation given by:

$$\text{sigma} = \sqrt{38}\ d$$

The normal procedure in an accelerator survey is to make a linear correction to the data, i. e. to distribute the closing error uniformly around the ring:

$$E_m = E'_m - (m/38)(E'_{39} - E_1)$$

Thus E_m is the corrected elevation of target m. However the very important point is that even though we have tied down the initial and final points of the survey, the intervening points are still subject to a random walk. In particular if we go one half way around the ring the standard deviation on the elevation measurement is roughly (careful analysis will give a slightly different value):

$$\text{sigma} \sim \sqrt{38/2}\ d$$
$$\sim 0.013 \text{ inches}$$

Thus on one measurement this point might be low by 1.5 sigma and on the next high by 1.5 sigma for a total swing of 0.039 inches, seemingly far outside our tolerances, but in actuality quite possible and quite impossible to eliminate or correct. However in the course of correcting blunders it has become customary to make local corrections to the magnet elevations to eliminate what we now believe are simply random walk effects in the measurement data. The result has been to present survey results of the AGS which show it to be very flat, an rms of 0.003 inches. These results are entirely spurious. The ring is very probably smooth (locally flat) to this accuracy, which is all that matters, but surely we have no knowledge that it is absolutly flat to this accuracy.

III. WALL TARGET ANALYSIS

The data were taken as follows:

i. The targets alone: 8/26/85;
ii. The targets and the magnets; 8/27-9/3/85;
iii. The targets alone: 9/19/85;
iv. The targets and the magnets: 9/23-10/2/85.

The magnets were adjusted between measurements iii and iv. We have four complete measurements of the wall targets from which we can calculate four separare sets of elevations. The absolute values of these measurements are not very interseting but we show in Figures 1,2,and 3 how measurements ii, iii, and iv differ from measurement i. Figure 1 shows swings of 0.010 to 0.015 inches which we must attribute to random errors and which are irreducible unless we go to a program of multiple measurements. Figure 2 shows a very large bump at target G-8, which corresponds very well with the removal of roofing blocks, which were partially restored by the time of Figure 3. Aside from this bump, these data represent four successive measurements of a set of fixed unmoving wall monuments, and display very well the limitations on our accuracy. Appendix I displays some Monte Carlo caculations to demonstrate the statistical nature of our results.

Figure 4 shows for targets G-3, G-8, and G-15 the time dependence of their positions. Eight roofing blocks centered at G-10 were removed on September 3 and replaced on September 27. The unloading has clearly produced a very large rise in target G-8 and some local oscillations around it. Historically, surveying is inevitably and necessarily closely correllated with shielding moves.

Since we have made four surveys we have four measurements of e(i,i+1) at each target. We can find the mean and standard deviation of each set of four measurements. Figure 5 shows the standard deviation at each station, and Figure 6 shows the frequency distribution of these numbers. Ignoring the bump at G-8, there is perhaps an upward slope to the data in Figure 5. Since each measurement started at A and went around the ring to L, this might suggest a fatigue factor, the errors being larger at the end of the job than at the beginning. We should cherish our surveyors more.

IV. MAGNET POSITIONS BEFORE ADJUSTMENT

Figure 7 shows the magnet positions determined by measurement ii before any magnets were moved. From sections C through D there is a 0.090 inch swing which is probably real. Future notes are planned which will seek to correlate this profile with the measured vertical orbits and which will examine the historical record of the elevation measurements.

The pitch of each magnet was determined by subtracting the downstream from the upstream elevation. The frequency distribution of the magnet pitches is plotted in Figure 8. The roll of each magnet was determined by subtracting the central elevation of each magnet from the mean of the upstream and the down stream elevations. The frequency distribution of the rolls is plotted in Figure 9. The tails on these distributions seem too broad for them to be good Gaussians but we might assume there is a central narrow distribution representing magnets initially well placed that have not been subseqently perturbed and a broader distribution of perturbed magnets. Then the half width at half height of the narrow distribution is 0.005 inches which is not bad, but the tails reach out as far as 0.020 inches, which is not very good. The magnets have all been repositioned so we can assume these tails have been cleaned up, but we have not been able to allocate the time necessary to remeasure them. Another problem of the roll is that we can not easily distinguish between a magnet that is rolled and a magnet that has sagged, since there are are only three survey points on top of a magnet. Systematic exploration of this possible problem will call for a large effort.

V. MAGNET POSITIONS AFTER ADJUSTMENT

Figure 10 shows the elevations of the magnets after their positions have been adjusted. This figure can be directly compared with Figure 7, showing the elevations before adjustment as the scales have been kept the same. Figure 11 is the same as Figure 10 except we have expanded the the vertical scale.

The magnets were positioned by taking the target elevations given by measurement iii as absolute and setting all the magnets flat relative to this survey. Since we can set magnets to few mills, a tabulation of the data at this point would indicate that the ring is flat to a few mills. However we now do a complete resurvey of the wall targets and the magnets. There is of course a random walk effect since neither measurement iii nor iv gives an absolutly accurate measurement. The differences between the wall target elevations for the two measurements are shown in Figure 12. With the present procedures this is the best we can do easily and these differences are reflected in Figures 10 and 11 which show the magnets positioned on the basis of measurement iii but plotted based on measurement iv. These results are also complicated by the moving of the roof blocks. In the past, and to some extent in the present survey, spuriously good results are produced at this point by moving magnets to smooth out the results of measurement iv.

In the near future we expect to check magnet J14 which looks unusually low, correcting individual magnets relative to their neighbors being a valid operation. Otherwise these results have been somewhat complicated by the roof block moves, but in general if we were to take another complete survey at the present time we would expect to get results to the same accuracy displayed here, though with perhaps a different profile resulting from a different random walk.

The point of this note has been that the dominent effect in the vertical survey is the random walk effect in our knowledge of the wall target elevations. Therefore the rms distribution of the magnets about some mean value is a relatively meaningless number, however, since PC programs give this result so readily we report here that sigma for Fig. 7 is 0.017 inches and for Fig. 10, 0.007 inches.

VI. RECOMMENDATIONS

The limitations on our accuracy discussed above are of a statistical nature and could be overcome by taking a large number of measurements. However the vertical survey of the AGS is not very easy to accomplish and we are always limited in our resouces. An alternate approach to using the wall targets, which are inherently fragile and which move with the tunnel walls, is to use the 24 primary survey monuments, which have heretofore been used solely for the radial survey even though they are all equipped with a bearing suitable for a vertical survey. These primary monuments are 20 foot steel pipes isolated from the floor. They should be more stable than the tunnel walls, though perhaps not as stable as the magnets which are on 50 foot piles. The present wall targets are more closely spaced than the primary monuments and therefore provde a more accurate measurement, but this drawback can be overcome by taking additional measurements. If we can establish the long term vertical stability of the primary monuments, than each survey can be averaged with all the previous surveys to greatly reduce the random walk effects discussed above and to greatly simplify the vertical survey since we can hope to have it based on 24 local but accurately known monuments. A key element in this scheme is accurately transferring an elevation from the top of the monument to the top of a magnet, a distance of a number of feet. The survey group is confident that they can do this.

The next step in this program is to invest at least one shift in evaluating the accuracy with which we can measure the monument elevations, and then several more shifts in establishing the elevations of the monuments. Once this is done we expect we will have laid the basis for a simple and long term solution to controlling the AGS vertical elevation.

VII. ACKNOWLEDGEMENTS

The authors of this note would like to gratefully acknowledge the hard and seriousness of purpose displayed by Frank Atkinson and his survey group for they have taken all the data and moved all the magnets discussed here and it is only through their carefull attention to detail that we can achieve any success in aligning the AGS. The particular individuals who worked on the 1985 survey are: Frank Karl, john Sullivan, Joseph Roecklein, Martin Boble, John Donnelly, Lewis Jiggetts, John Slavik, Daniel McCafferty, Robert Glasman, Robert Tallon, John Scheblein, and Edmund Kramp.

FIGURE CAPTIONS

FIGURE 1. The absolute elevations of the wall targets as determined in measurement i subtracted from those determined in measurement ii. For these plots, a set of 36 uniformly spaced targets is used.

FIGURE 2. The same as Figure 1 except for measaurement iii instead of measurement ii. The large spike at G-8 is due to the removal of roof blocks.

FIGURE 3. The same as Figure 1 except for measurement iv instead of measurement ii. The roofing blocks are still moving in the G and H areas.

FIGURE 4. The target elevations in G as a function of time. TG- 3 does not move. Five roofing blocks centered at SS G-7 were removed on Sept. 4 and were replaced on Sept. 19 and 20. The measurements in G were actually made on the 20th, not the 19th. The G-8 target is mounted on the walls which support the roof blocks. There is plainly a 0.040 inch shift in G-8.

FIGURE 5. The standard deviation calculated from the four measurements made at each target.

FIGURE 6. The frequency distribution of the standard deviations from FIGURE 5.

FIGURE 7. The elevations of the upstream pad on each magnet as determined by measurement ii before any magnets were adjusted.

FIGURE 8 The frequency distribution of the piches measured before adjustment. The pitch of each magnet is defined as the elevation of the downstream pad minus the elevation of the upstream pad.

FIGURE 9 The frequency distribution of the magnet rolls measured before adjustment. The roll is defined as the mean of the elevations of the upstream and the downstream pads minus the elevation of the central pad. This definition does not include a sign correction as the magnet back legs switch from inside to outside the ring.

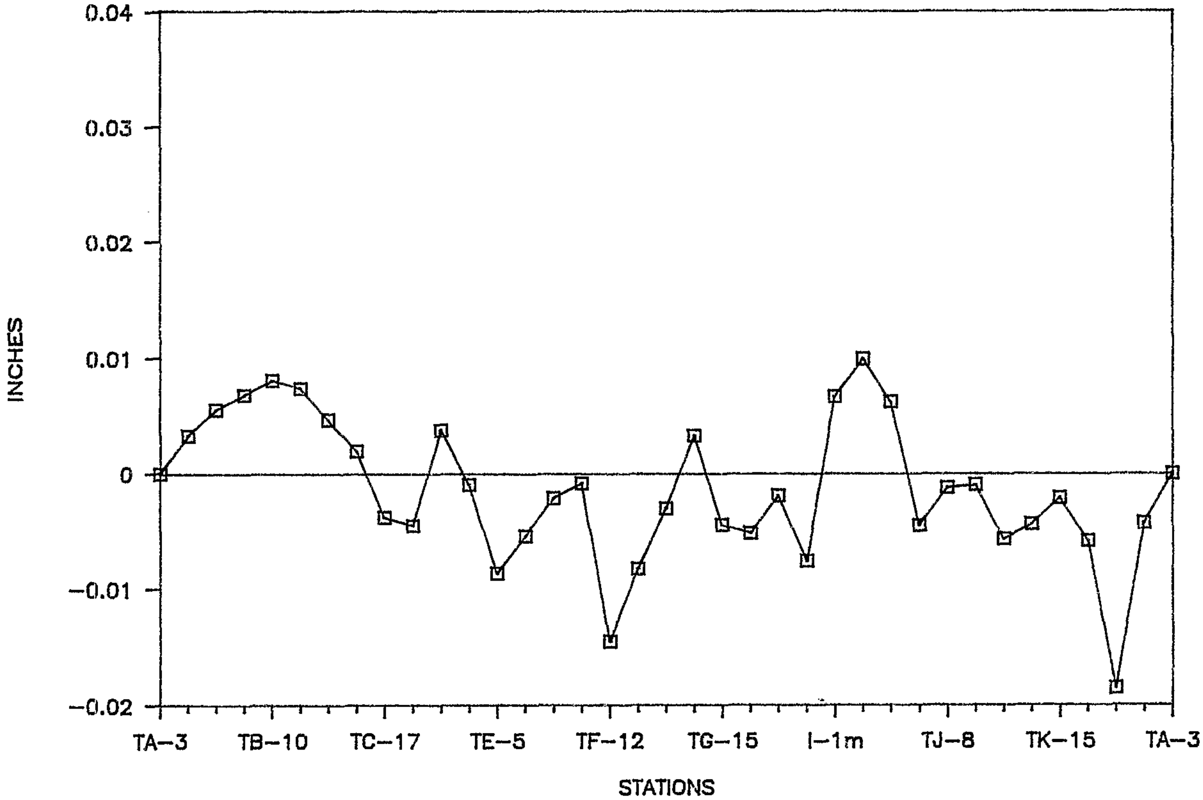
FIGURE 10. The elevations of the upstream pad on each magnet as determined by measurement iv after the magnets were adjusted.

FIGURE 11. Same as FIGURE 10 but with an expanded vertical scale.

FIGURE 12. The absolute elevations of the wall targets as determined in measurement iii subtracted from those determined in measurement iv.

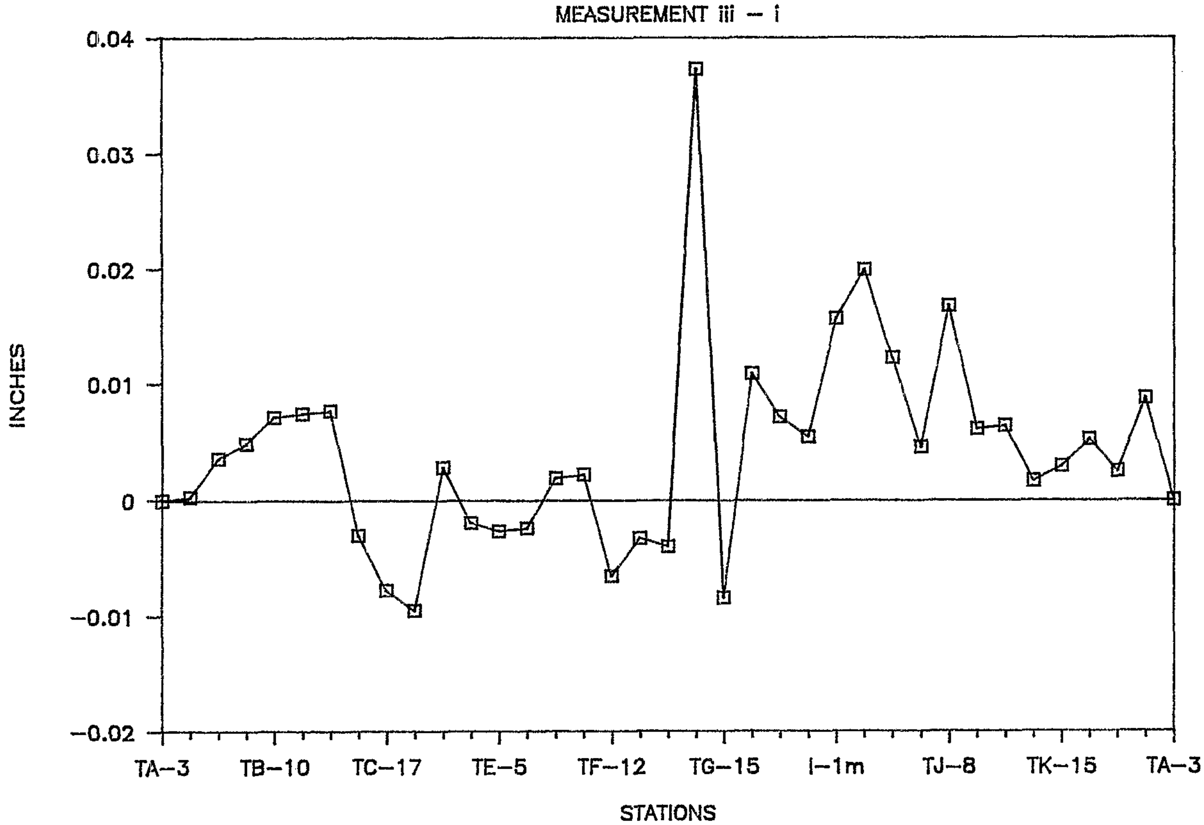
WALL TARGET DIFFERENCES Figure 1

MEASUREMENT ii − i

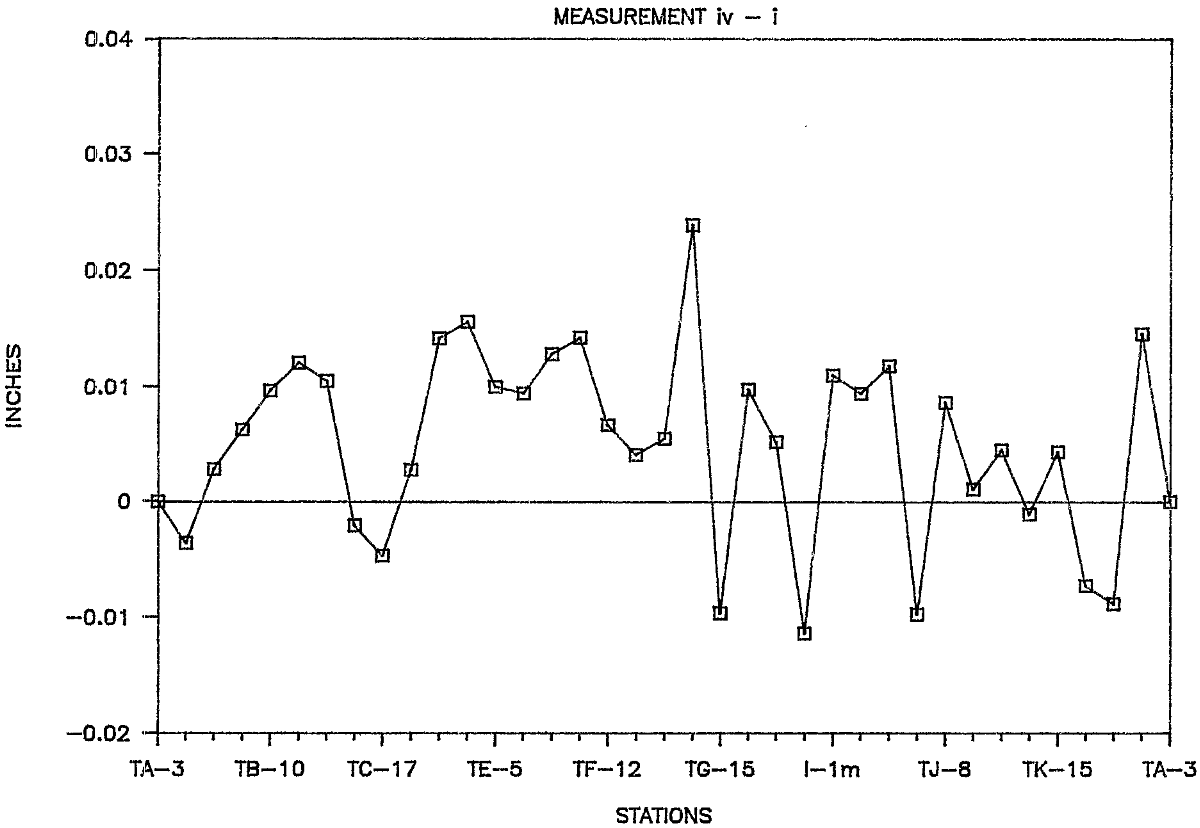


WALL TARGET DIFFERENCES Figure 2

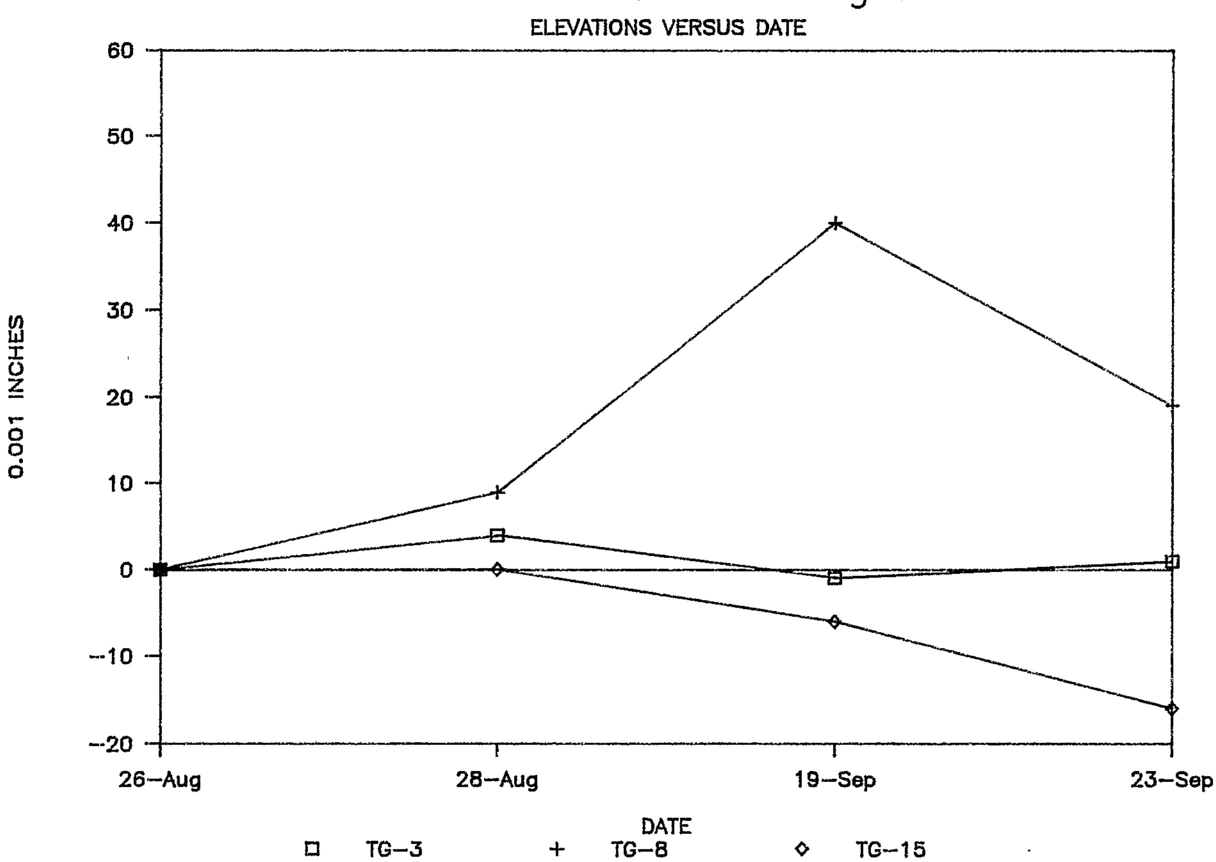
MEASUREMENT iii − i

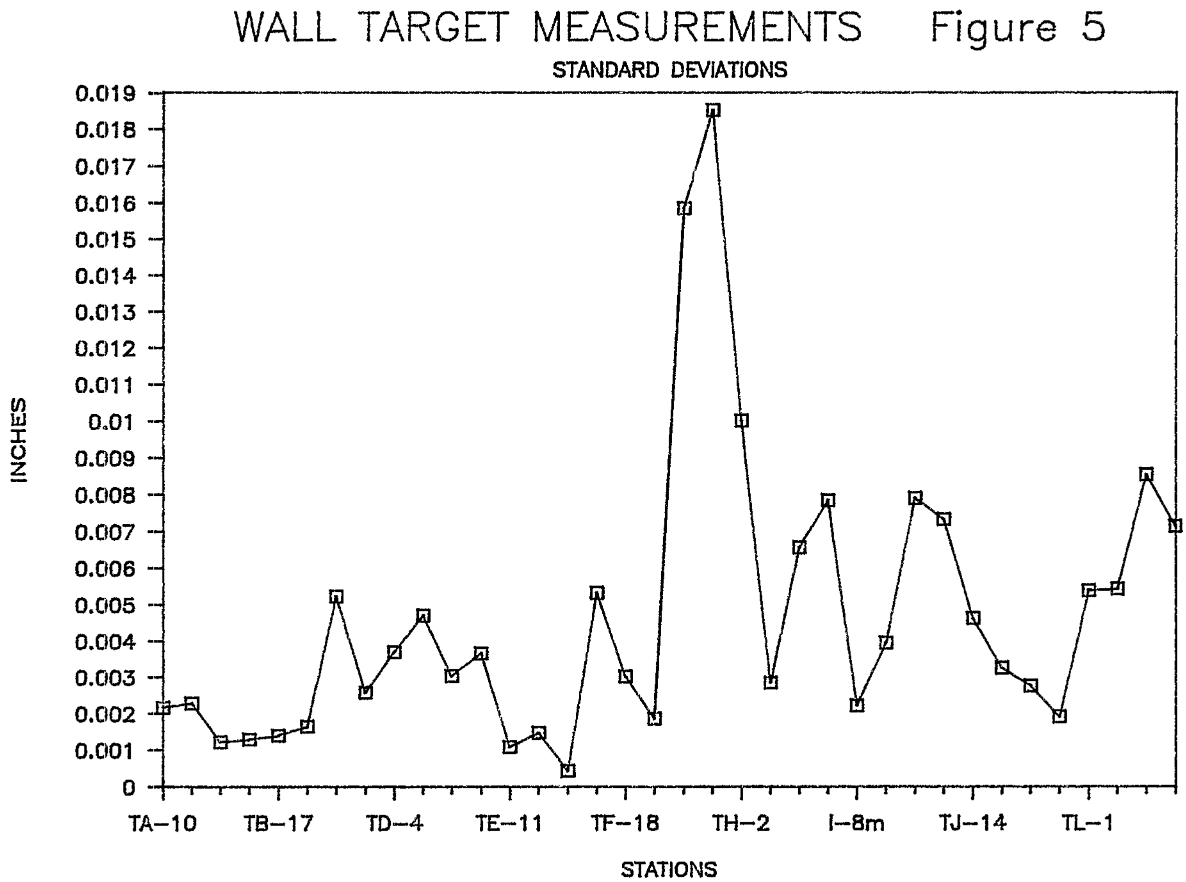


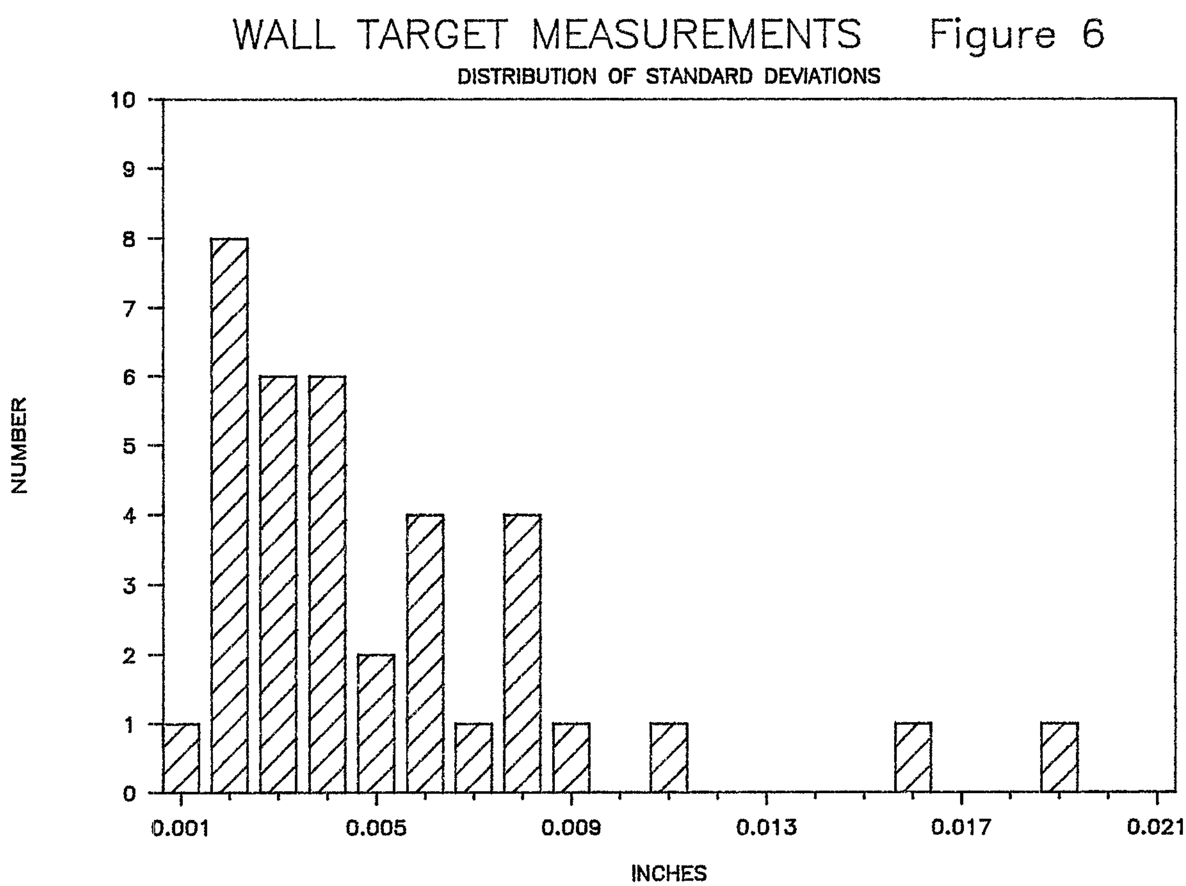
WALL TARGET DIFFERENCES Figure 3



TARGET MOVEMENT Figure 4

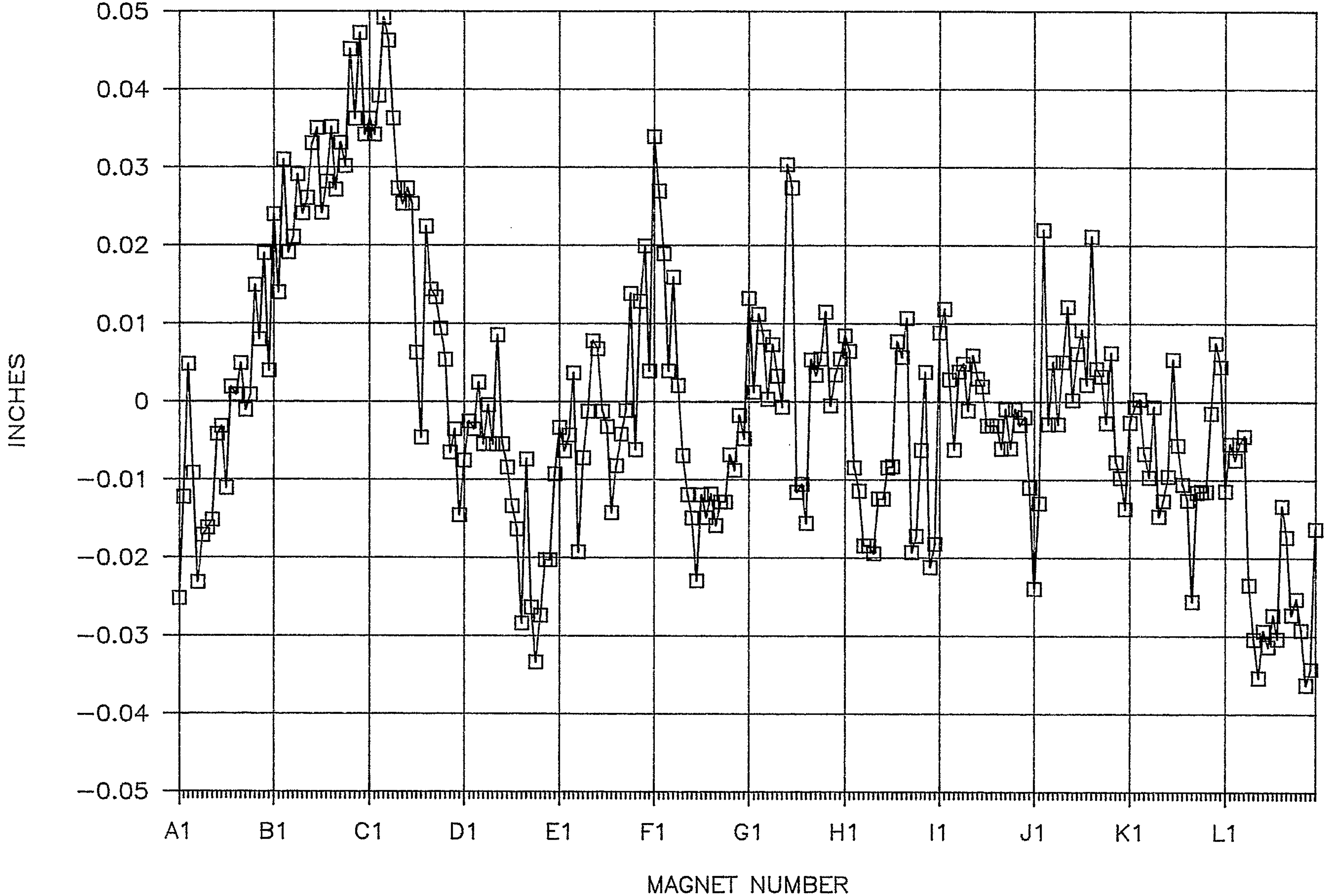



WALL TARGET MEASUREMENTS Figure 5
STANDARD DEVIATIONS
INCHES
0.019
0.018
0.017
0.016
0.015
0.014
0.013
0.012
0.011
0.01
0.009
0.008
0.007
0.006
0.005
0.004
0.003
0.002
0.001
0
TA-10
TB-17
TD-4
TE-11
TF-18
TH-2
I-8m
TJ-14
TL-1
STATIONS


WALL TARGET MEASUREMENTS Figure 6
DISTRIBUTION OF STANDARD DEVIATIONS
NUMBER
10
9
8
7
6
5
4
3
2
1
0
0.001
0.005
0.009
0.013
0.017
0.021
INCHES

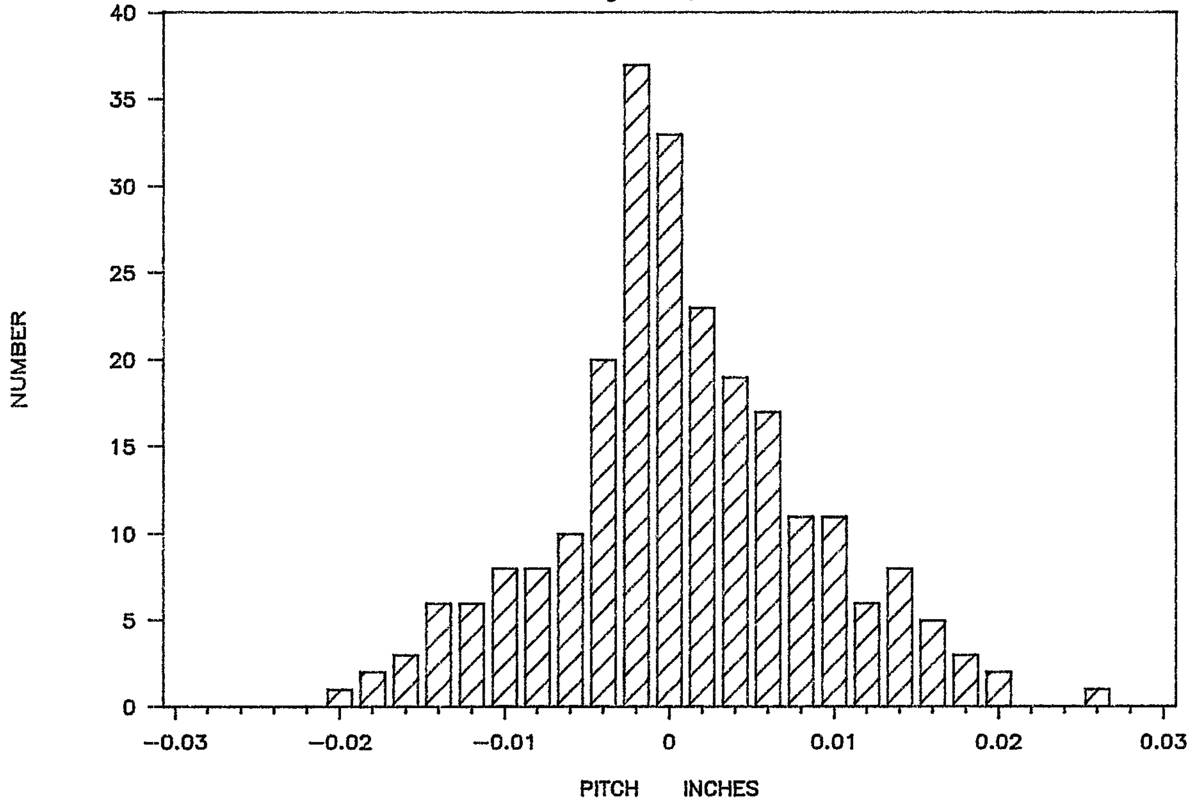
MAGNET ELEVATIONS Figure 7

August 27, 1985



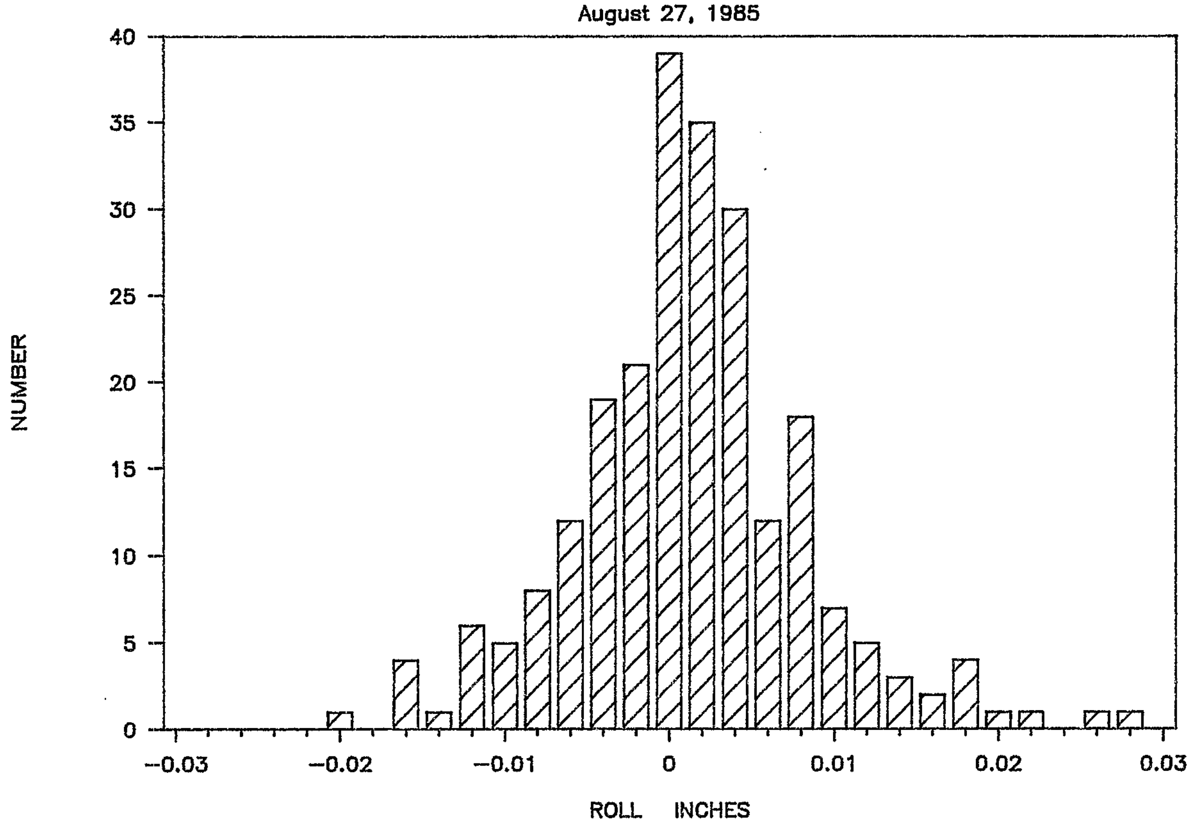
PITCH DISTRIBUTION Figure 8

August 27, 1985



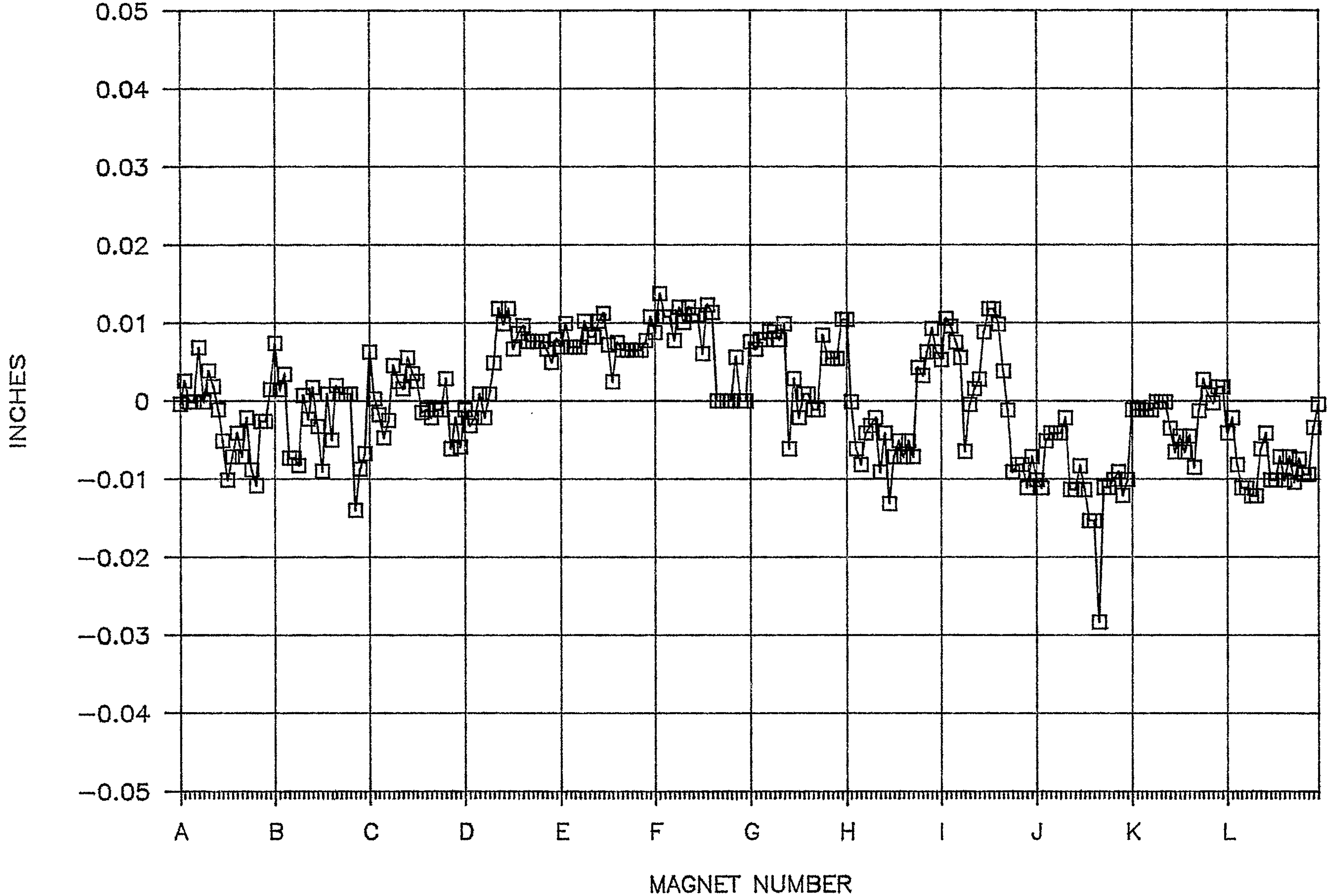
ROLL DISTRIBUTION Figure 9

August 27, 1985



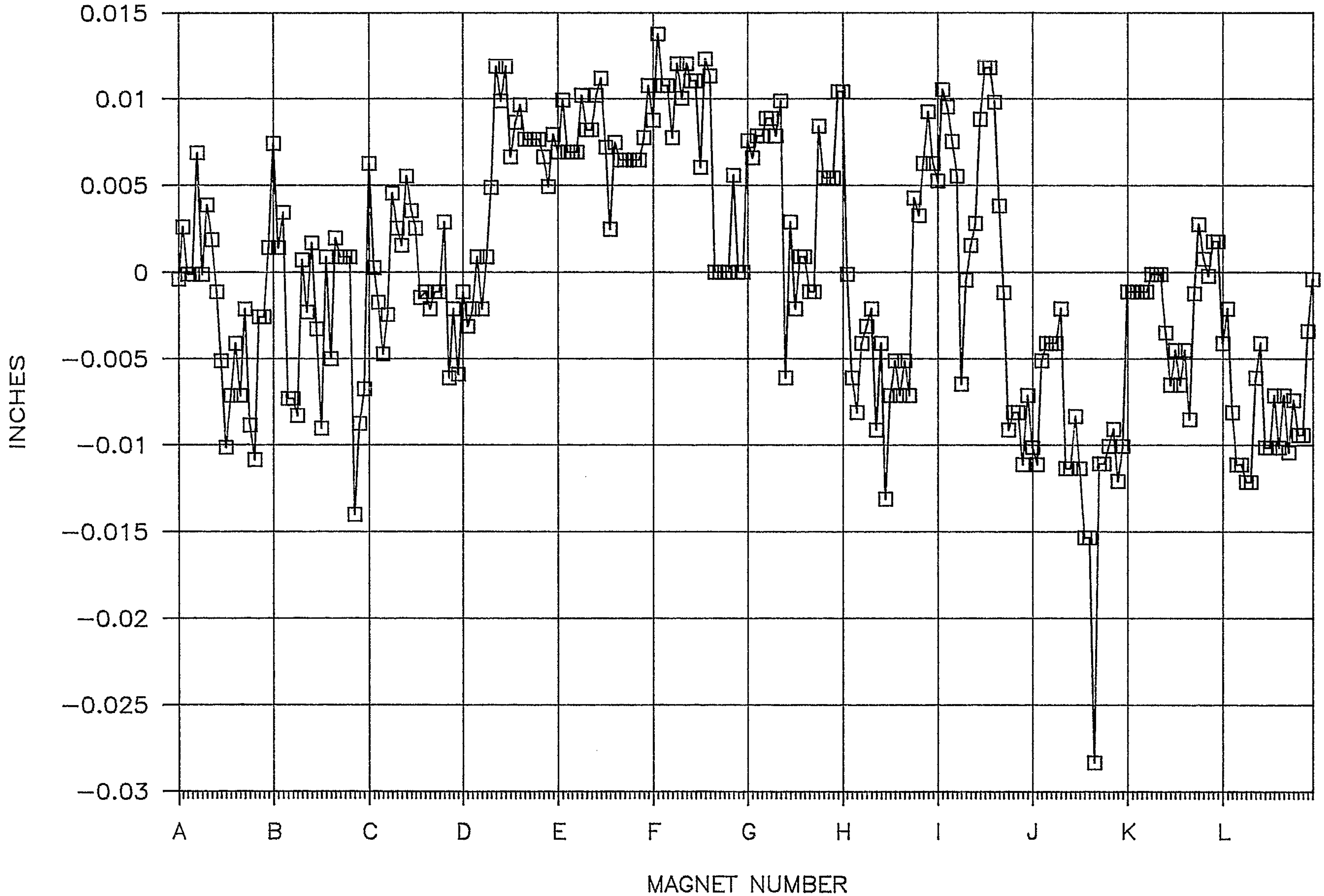
MAGNET ELEVATIONS Figure10

October 2,1985



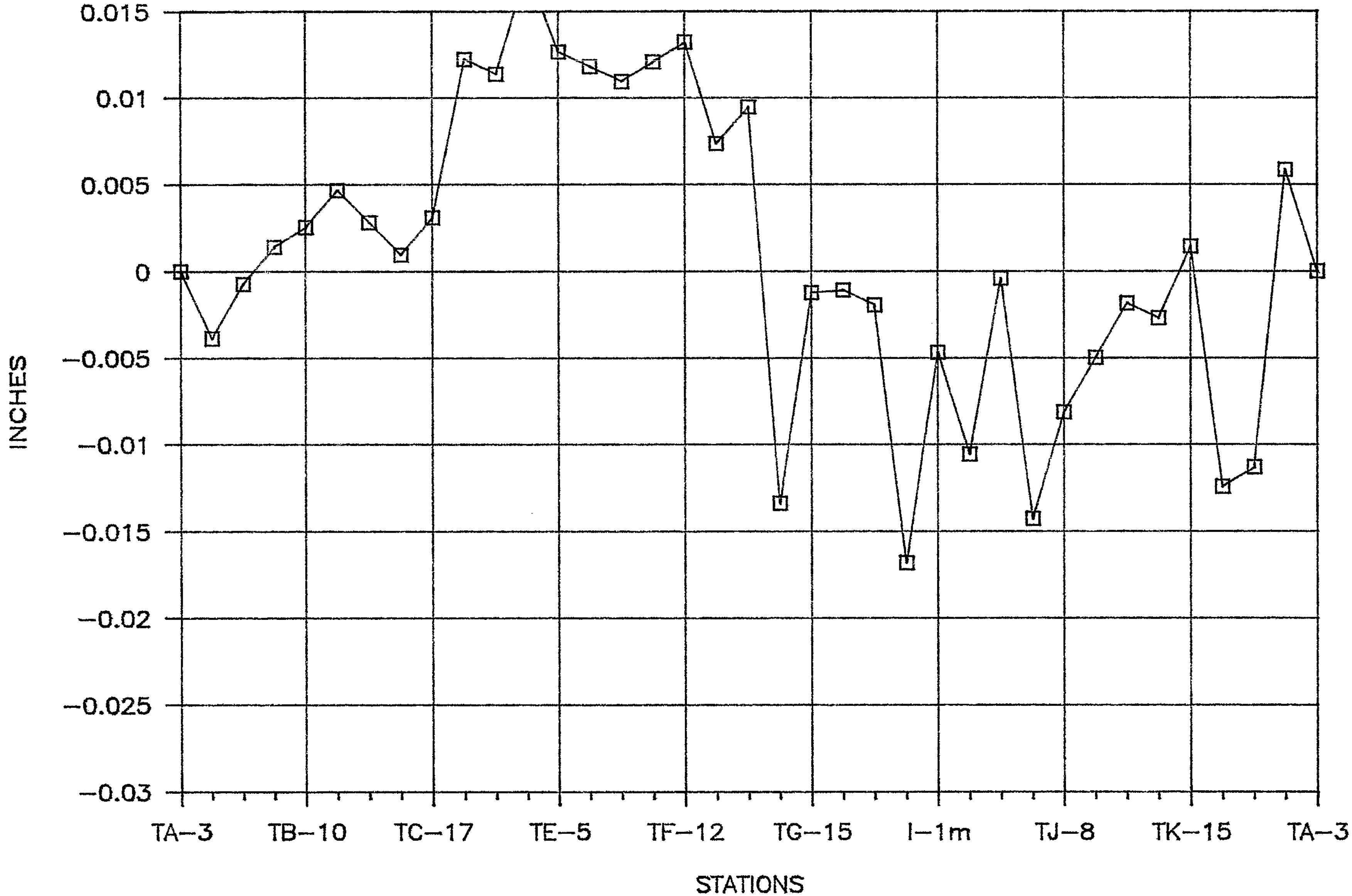
MAGNET ELEVATIONS Figure 11

October 2,1985



WALL TARGET DIFFERENCES Figure 12

MEASUREMENT iv – iii



APPENDIX

1. MONTE' CARLO OF SURVEY PROCEDURE

Using the random number generator

$$\left(\sum_{i=1}^{12} R(i)-6\right)\cdot d,$$

where R(i) is a random number between 0 and 1 and d is the rms uncertainty per measurement, an approximately gaussian random distribution is achieved with a standard deviation of d.

This was used to simulate the random walk behavior in surveying the wall targets. The data was then corrected for the closure error in the same manner as was the survey data . Figures A-1 through A-10 are ten independent runs of the procedure. Figure A-11 is the sum average of these runs. For this data d was taken to be 0.0035 inches and h(0) was taken to be 0.

2. FOURIER' ANALYSIS OF MONTE' CARLO DATA

The harmonics were determined using a numerical methode:

The coefficients of the series

$$f(x)=a_0+a_1\cos(kx)+...+a_n\cos(nkx)+b_1\sin(kx)+...+b_n\sin(nkx)$$

are, assuming the interval from 0 to 2π is divided into r equal parts,

$$a_m=(2/r)\sum_{x=1}^{r} f(x)\cos(mkx),$$

$$b_m=(2/r)\sum_{x=1}^{r} f(x)\sin(mkx),$$

and

$$a_0=(1/r)\sum_{x=1}^{r} f(x);$$

where,

x is the value of the coordinate (from 1 to r),

f(x) is the value of the function corresponding to position x,

m=1,2,...,n is the harmonic number,

and, $k=2\pi/r$.

The magnitude of a harmonic is :

$$H_m=[a_m^2+b_m^2]^{1/2}$$

and the phase is

$$\theta=\arctan[b_m/a_m].$$

For the monte' carlo data ;

r=37.

APPENDIX FIGURE CAPTIONS

FIGURE A-1 THROUGH A-10:
These are the ten monte' carlo runs.

FIGURE A-11:
The ten runs averaged.

FIGURE A-12:
Mean elevation of each run plotted vs Run number, with the elevation of the 10 run mean.

FIGURE A-13:
Standard Deviation (from mean) vs Run number. The standard deviation for the ten run average is shown.

FIGURE A-14 THROUGH A-17:
These are examples of the results of the harmonic analysis. Figure A-17 shows the harmonics on the ten run average.

FIGURE A-18:
To test the accuracy of the harmonic analysis the data was reproduced from the harmonics and plotted on top of the data. The boxed points represent the data and the + points represent the reproduction of it from the harmonics.

FIGURE A-1

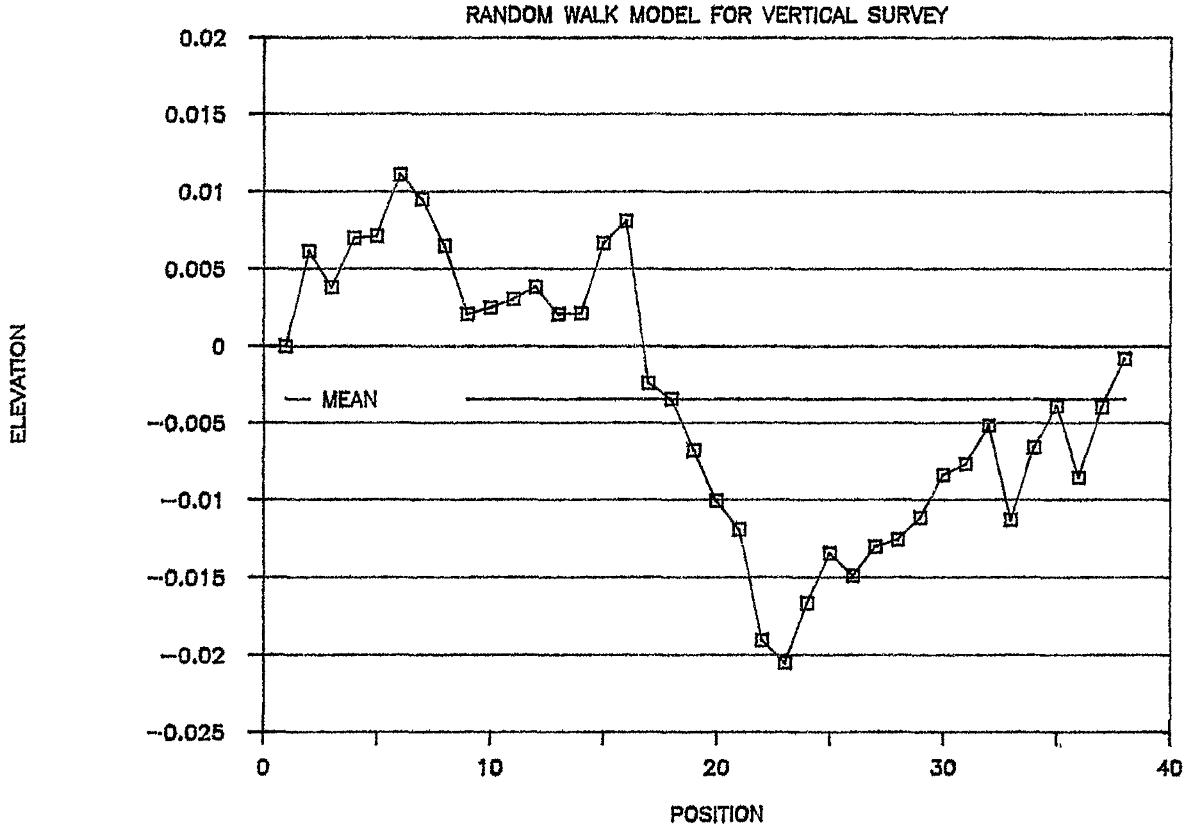


FIGURE A-2

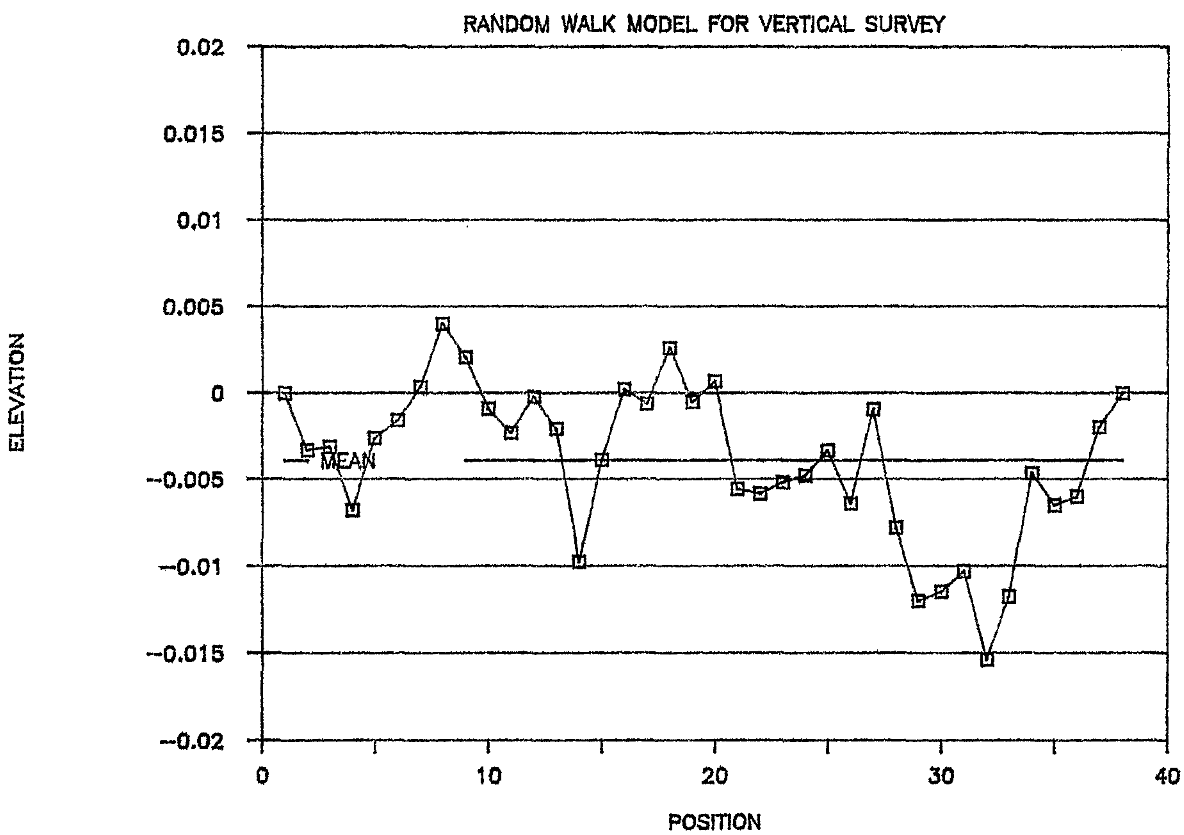


FIGURE A–3

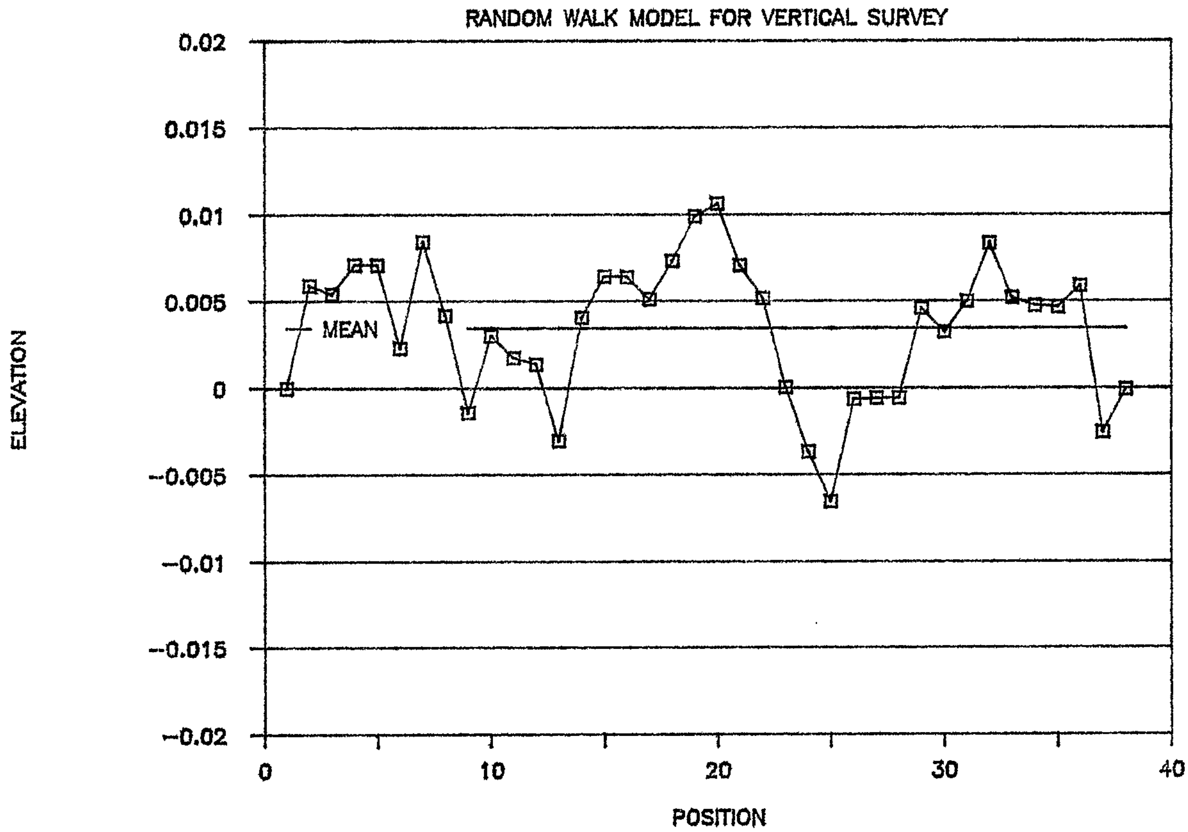


FIGURE A–4

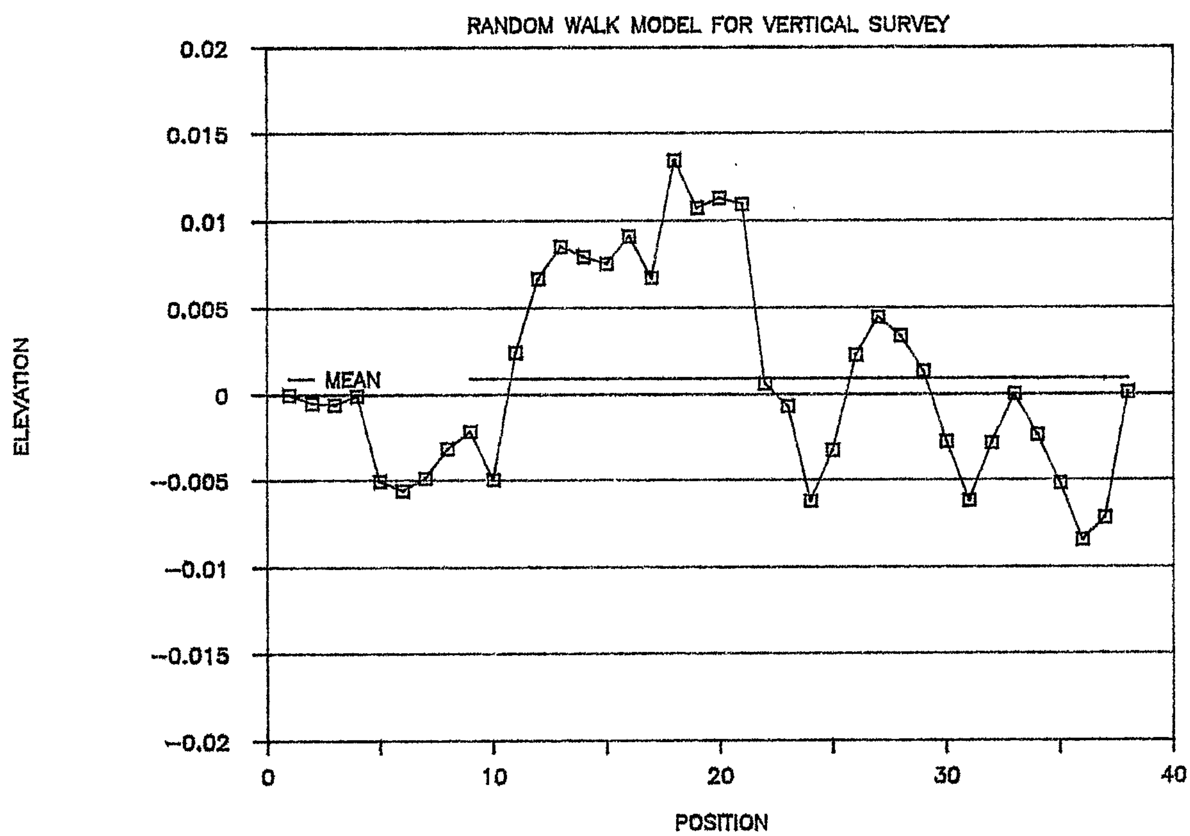


FIGURE A-5

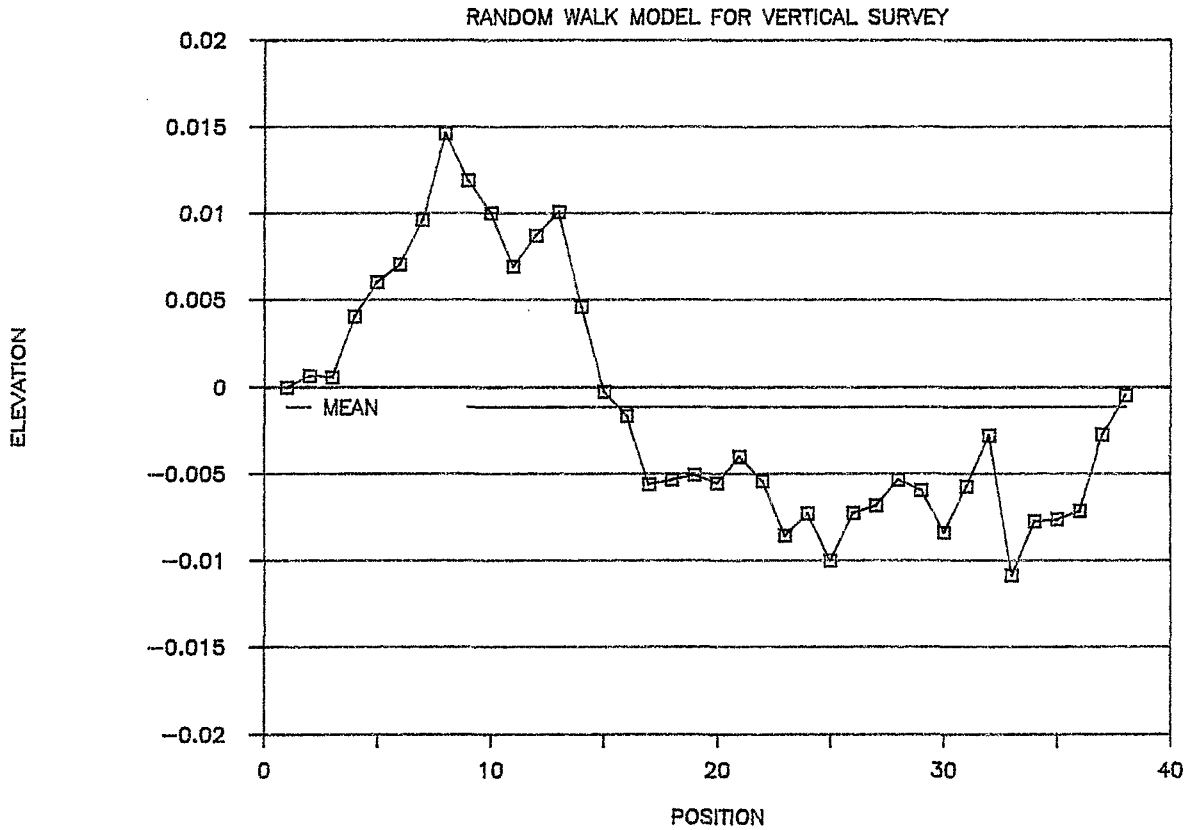


FIGURE A-6

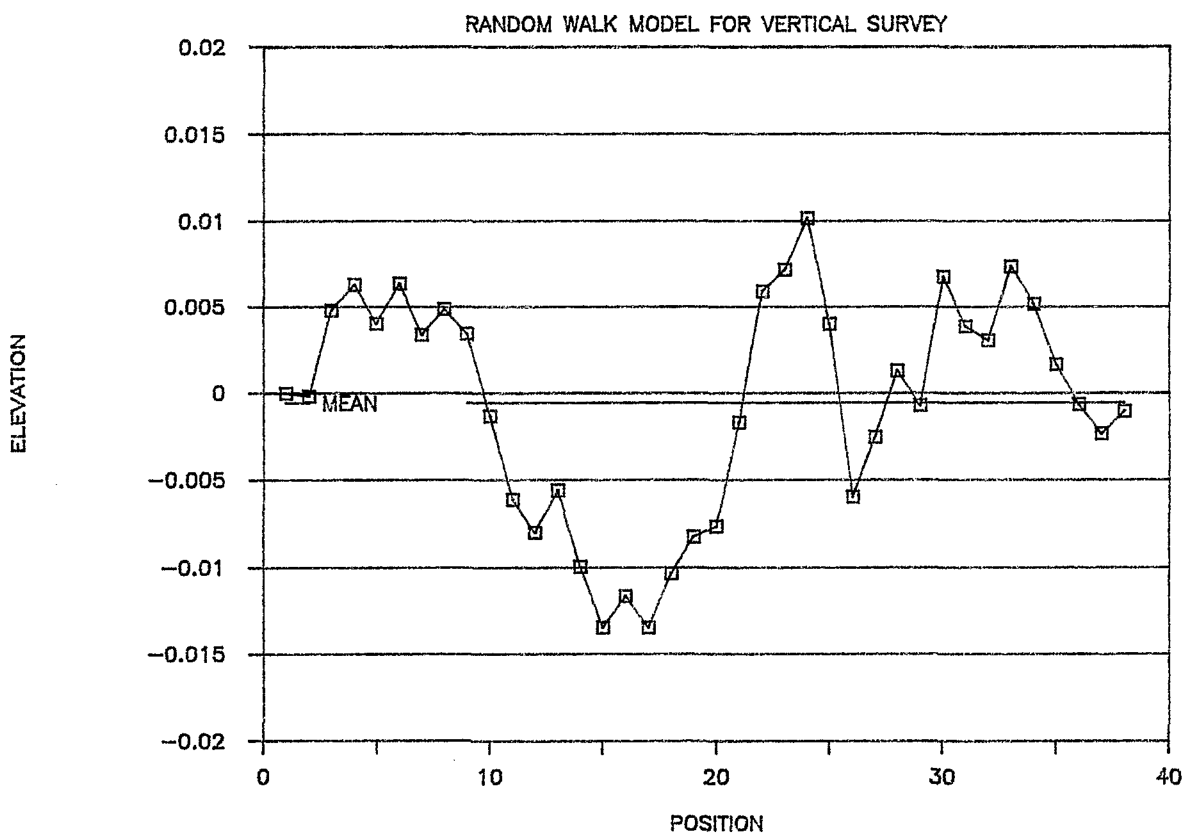


FIGURE A-7

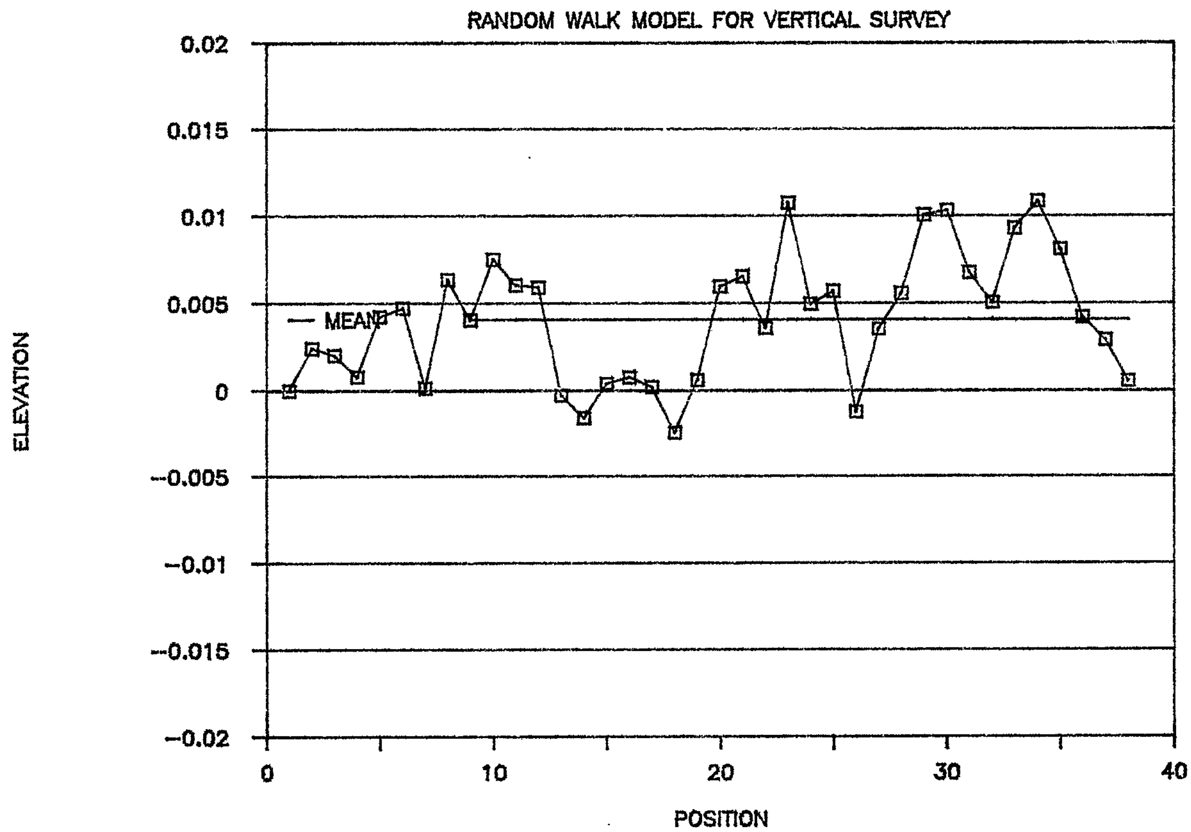


FIGURE A-8

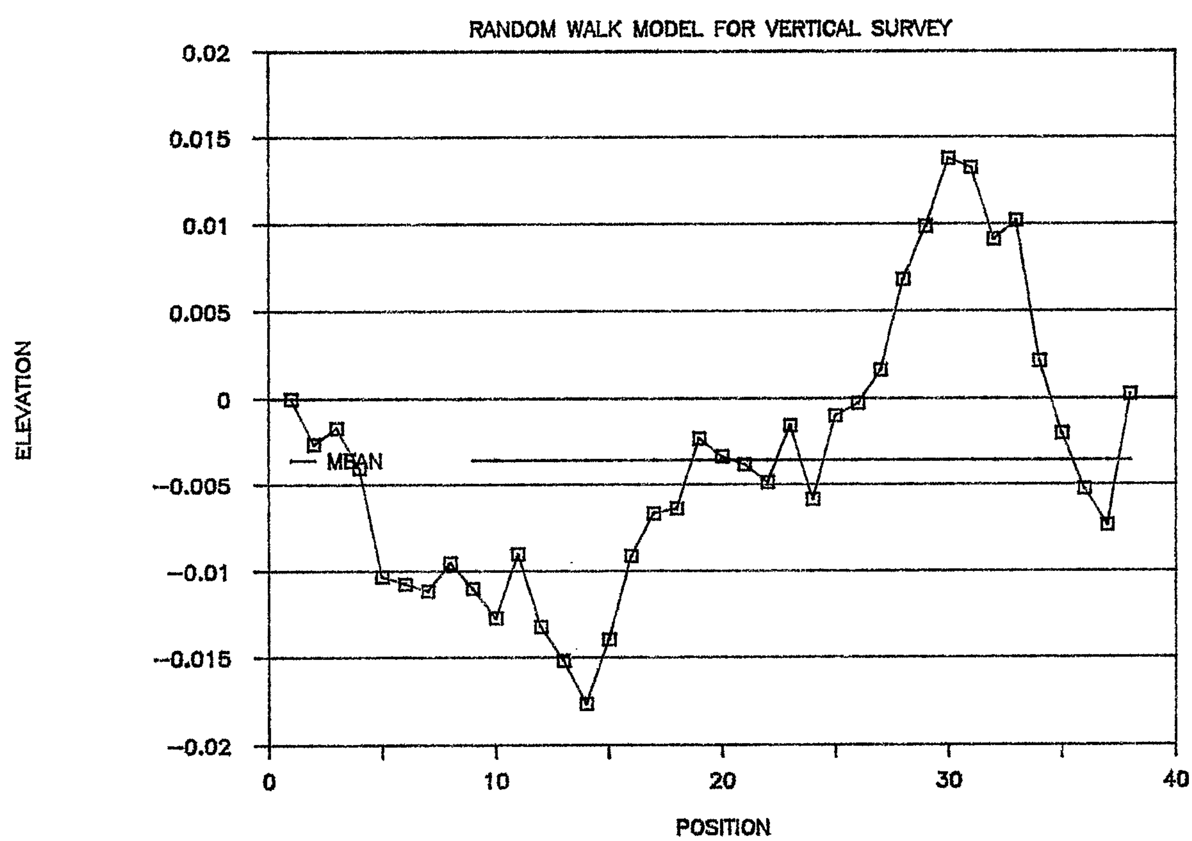


FIGURE A-9

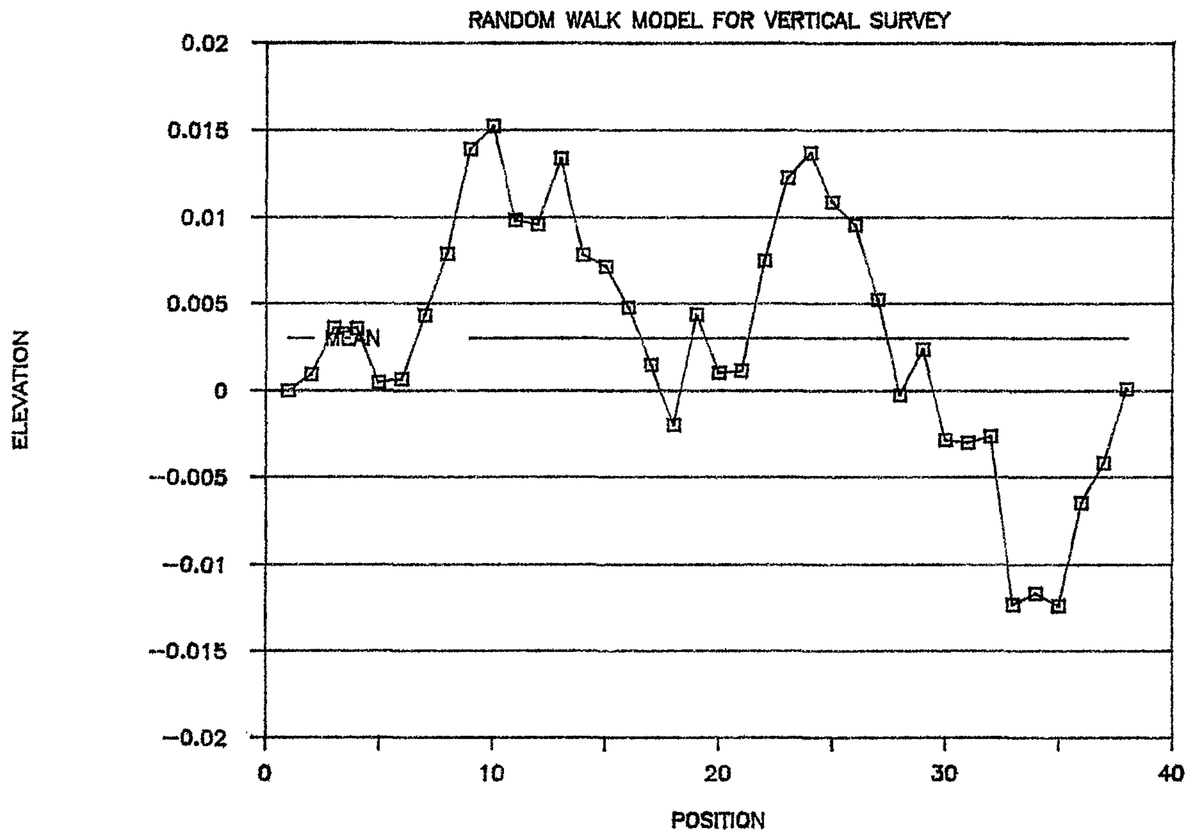


FIGURE A-10

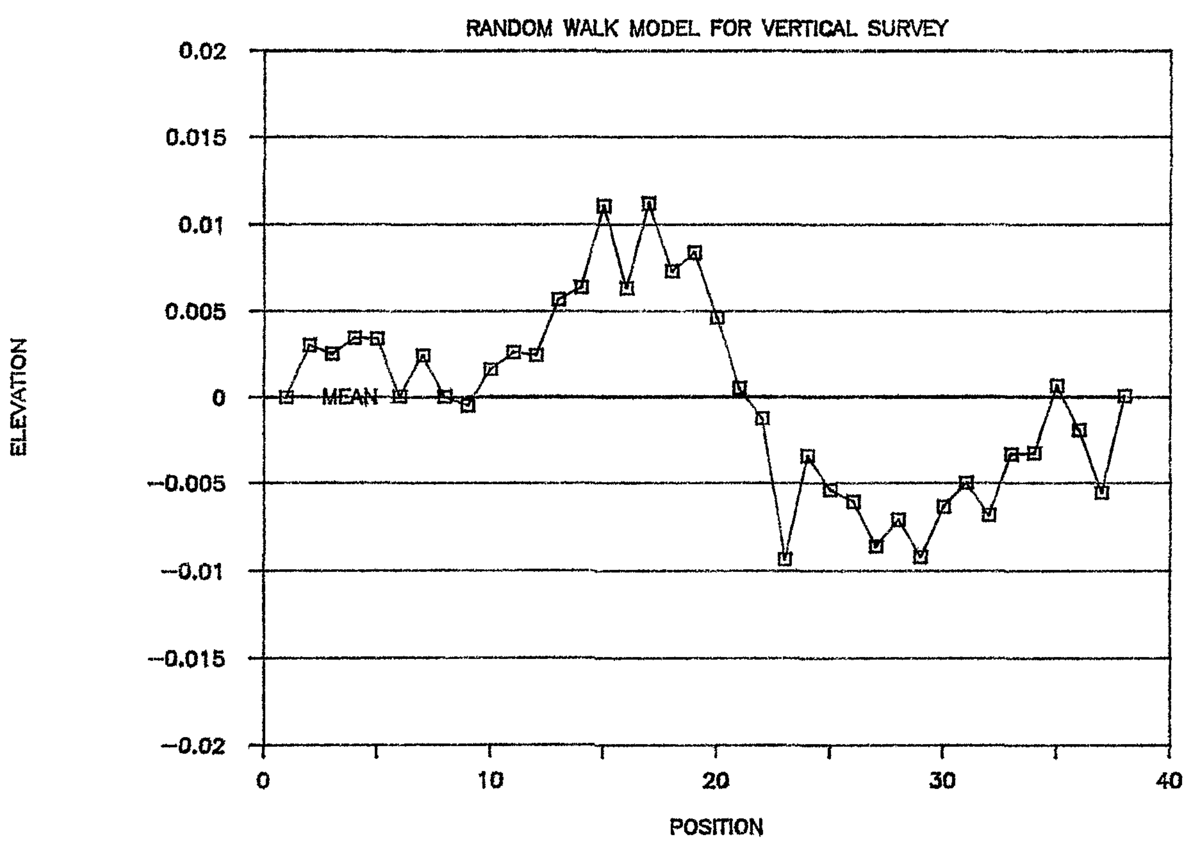


FIGURE A-11

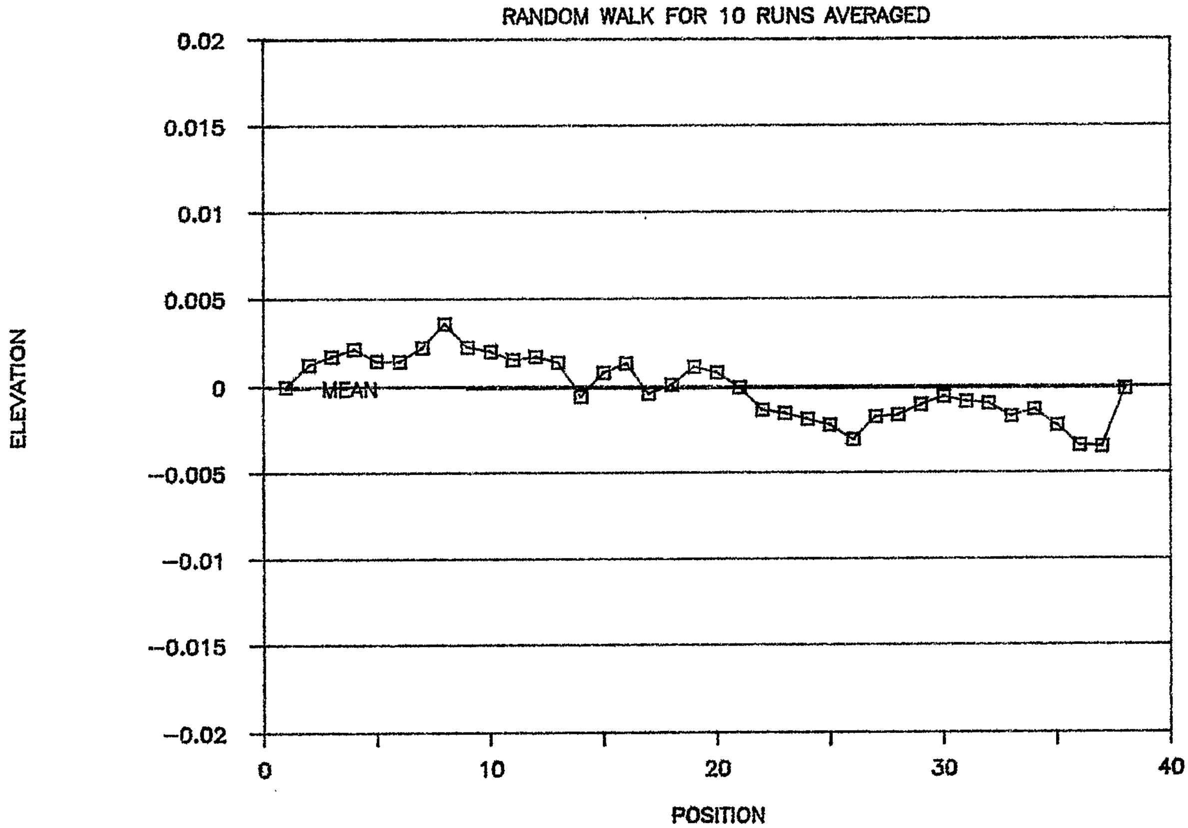


FIGURE A-12

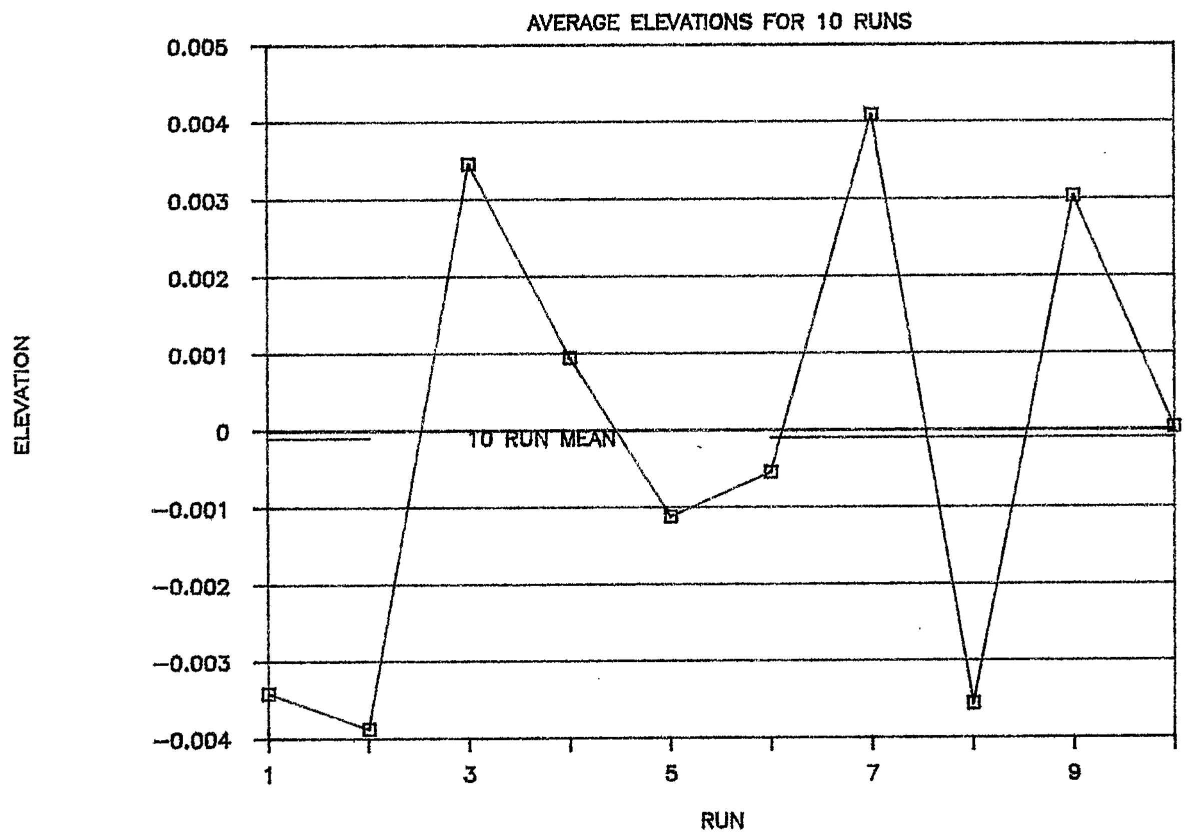
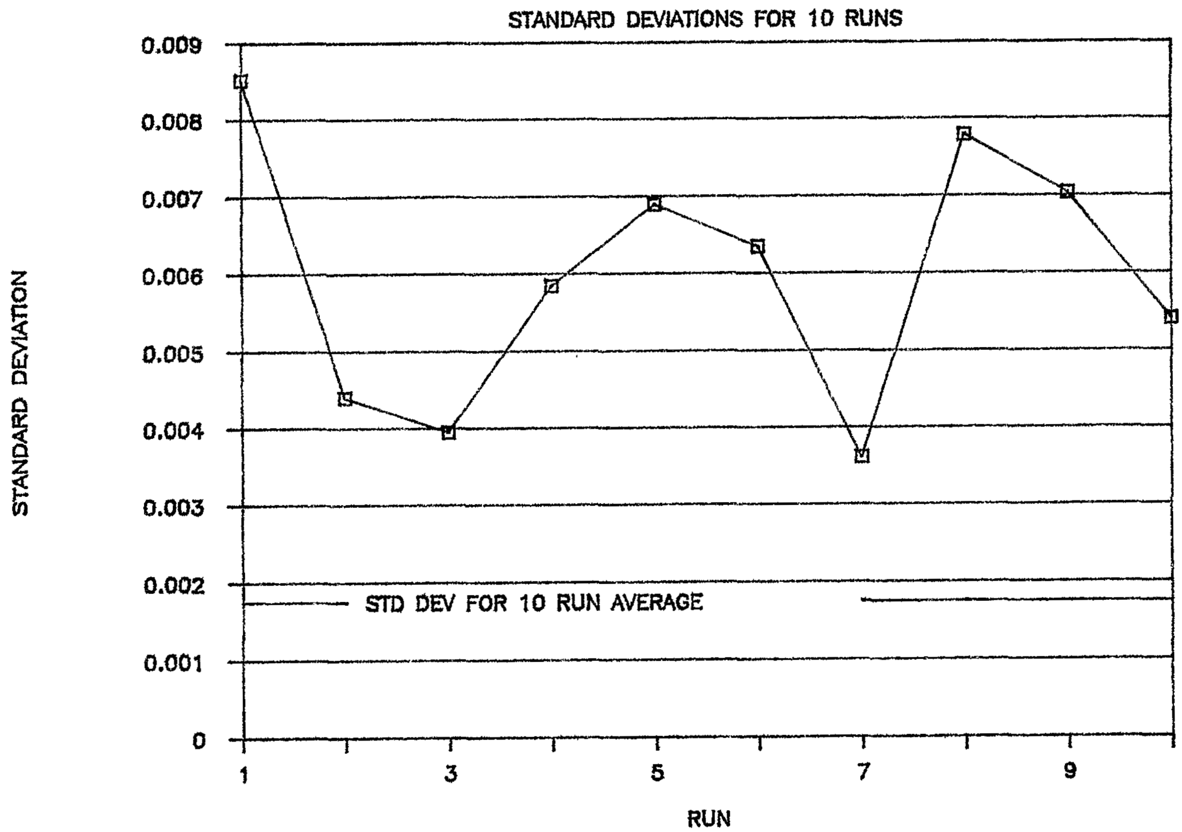


FIGURE A-13



STANDARD DEVIATIONS FOR 10 RUNS
0.009
0.008
0.007
0.006
0.005
0.004
0.003
0.002
0.001
0
STANDARD DEVIATION
STD DEV FOR 10 RUN AVERAGE
1
3
5
7
9
RUN

FIGURE A–14

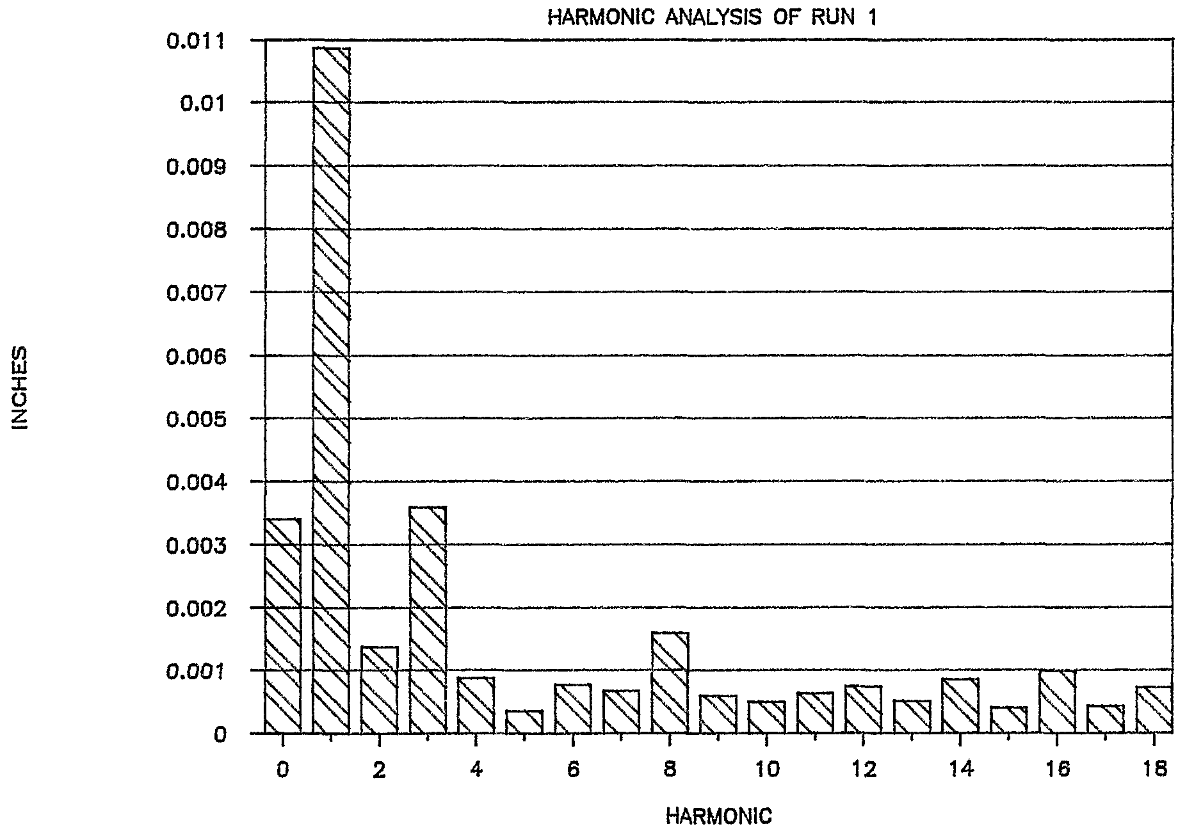


FIGURE A–15

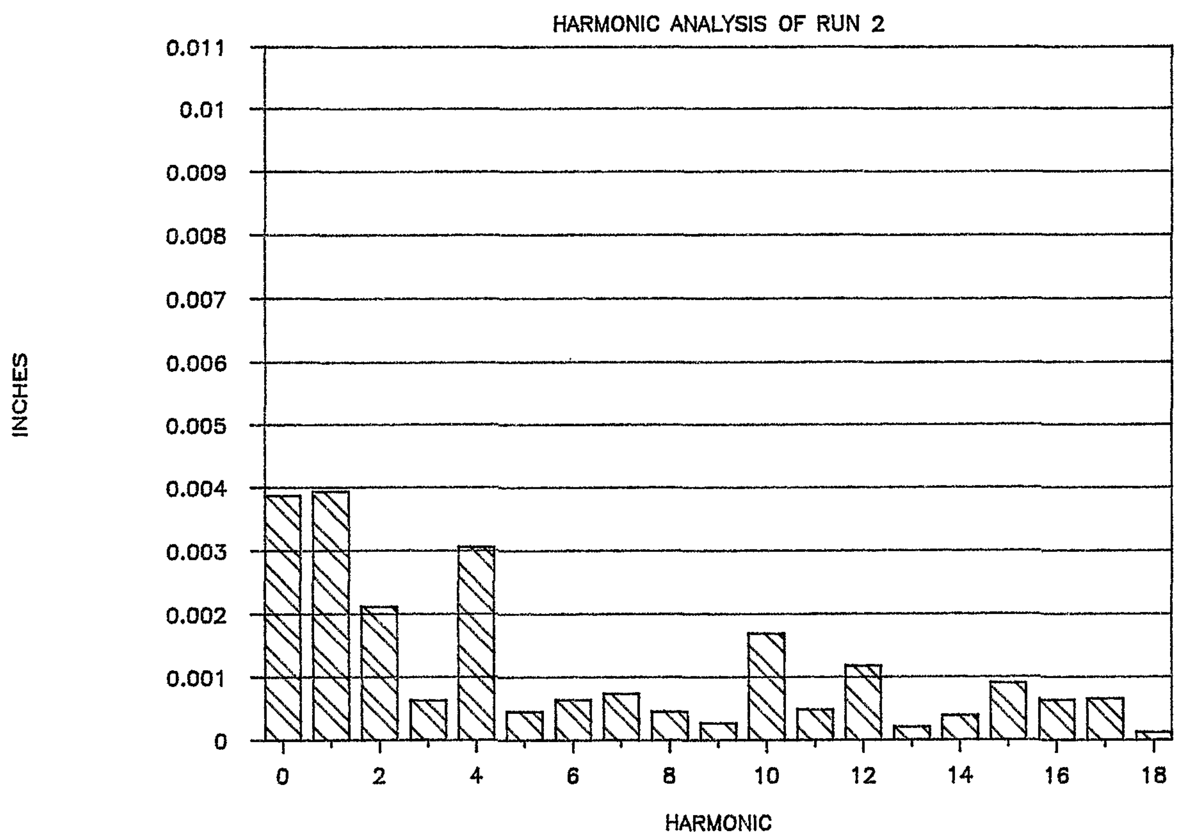


FIGURE A—16

HARMONIC ANALYSIS OF RUN 10

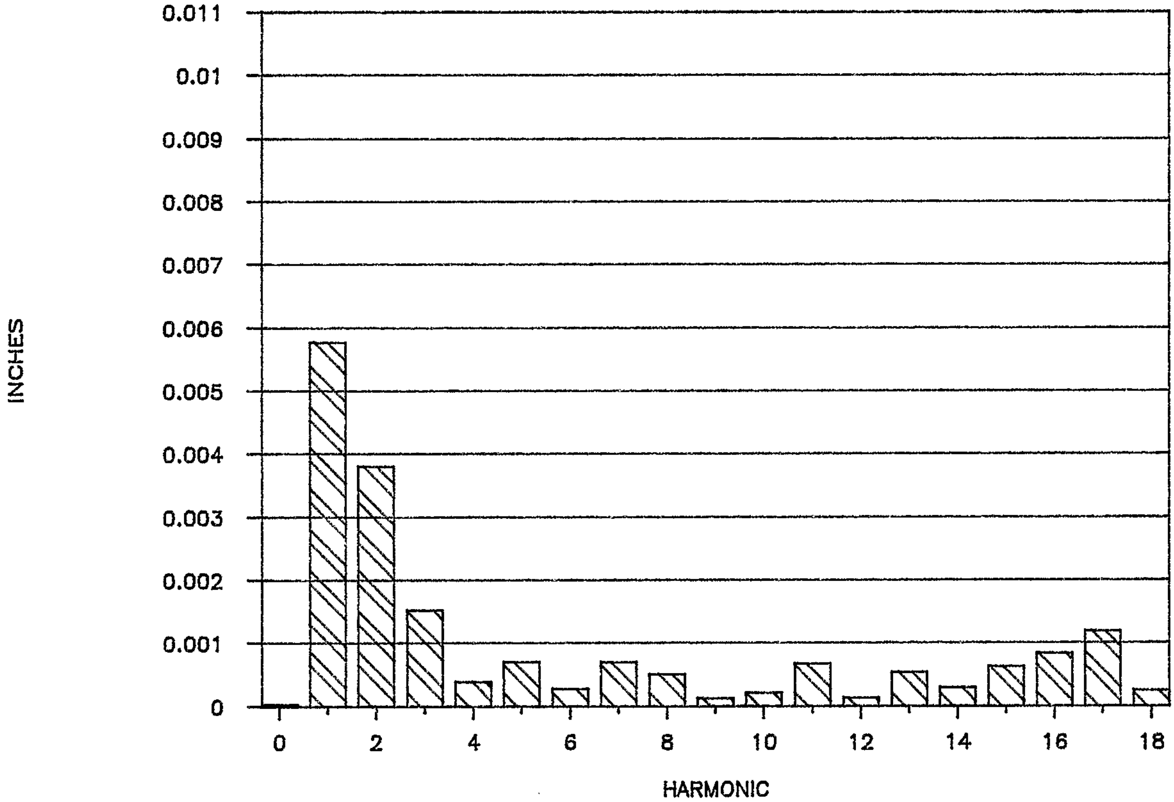


FIGURE A—17

HARMONIC ANALYSIS OF 10 RUNS AVERAGE

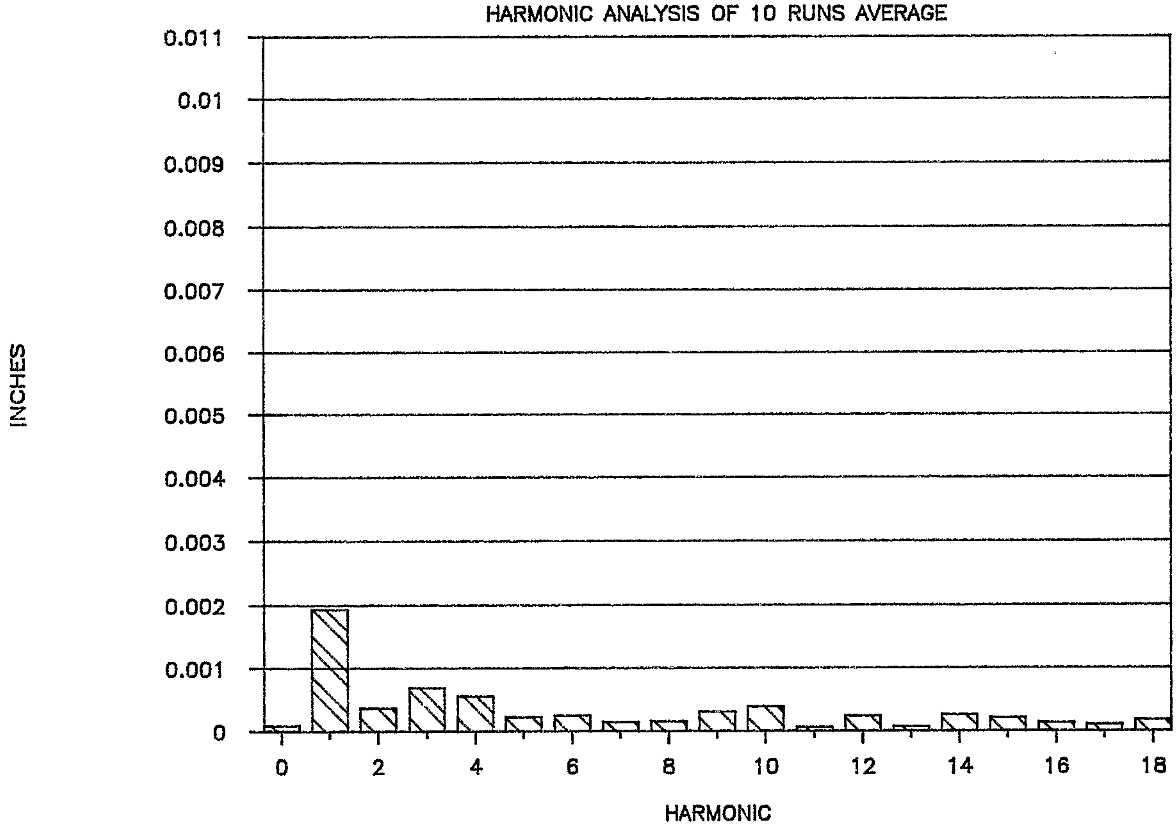
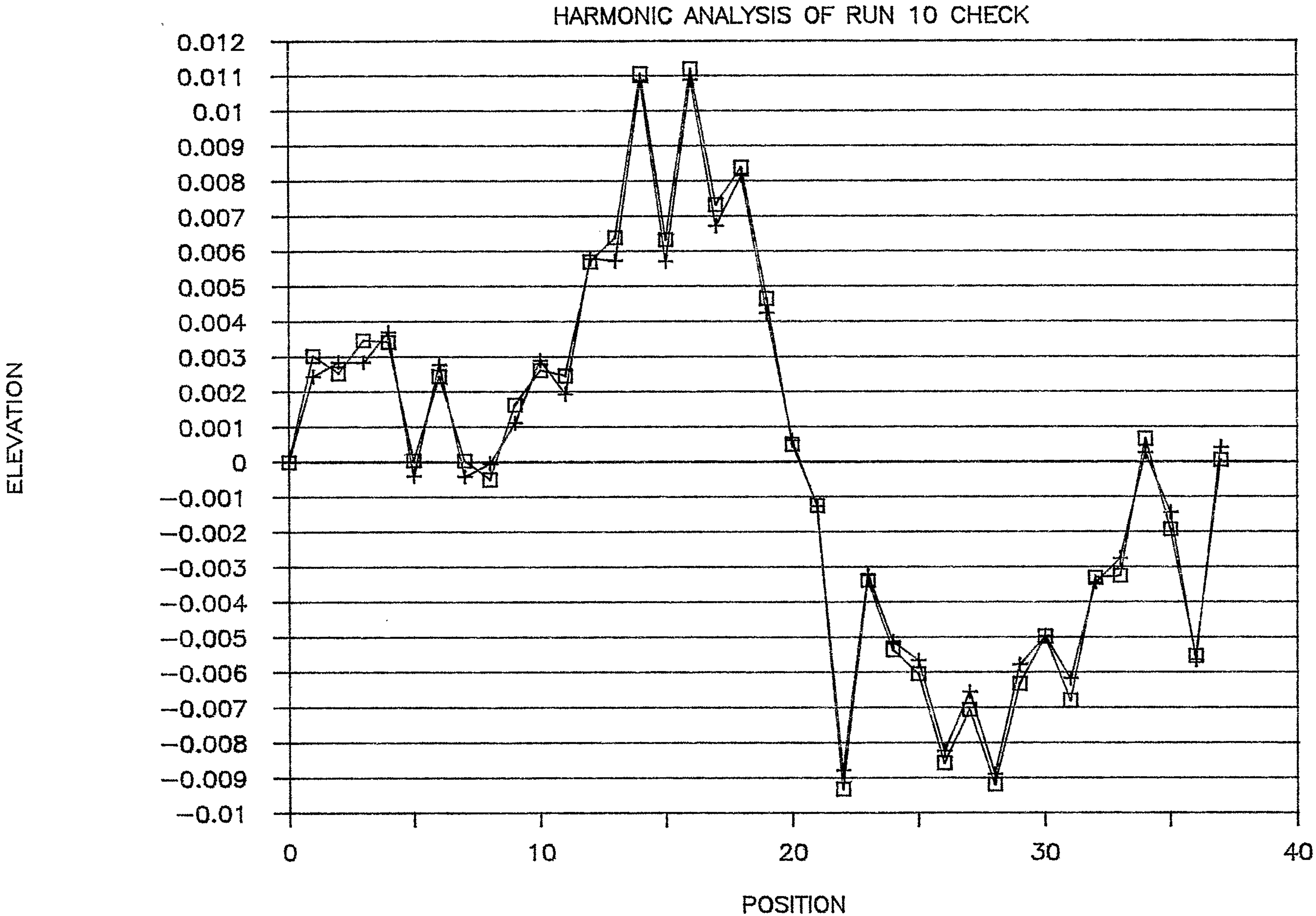


FIGURE A-18



HARMONIC ANALYSIS OF RUN 10 CHECK
0.012
0.011
0.01
0.009
0.008
0.007
0.006
0.005
0.004
0.003
0.002
0.001
0
−0.001
−0.002
−0.003
−0.004
−0.005
−0.006
−0.007
−0.008
−0.009
−0.01
ELEVATION
0
10
20
30
40
POSITION

Diagram 1: Location of Pads.
-TOP VIEW OF MAGNETS-

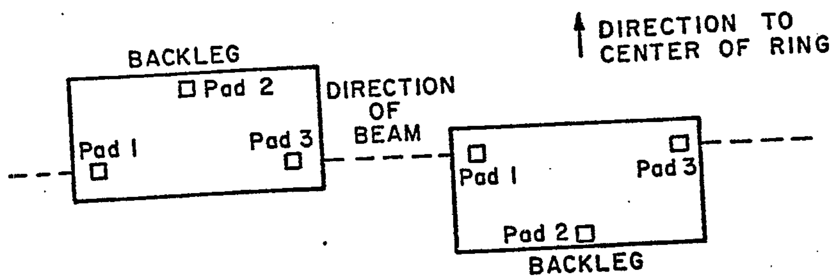


Diagram 2: Convention for Pitch (Pad3-Pad1).
-SIDE VIEW OF MAGNET-

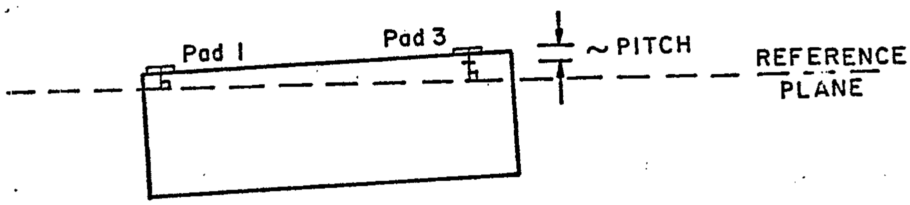


Diagram 3: Convention for Roll [1/2(Pad1+Pad3)-Pad2].
-VIEW OF DOWNSTREAM END OF MAGNET LOOKING UPSTREAM-