Evaluation of LVDT Units for the GBT

D. Schiebel, B. Vance, C.J. Salter

July 24, 1992

1 Introduction

The active surface of the GBT is designed to have three basic modes of operation. Firstly, the basic surface setting, as delivered by the contractors and up-dated by holography. At the next level of complexity, the open-loop system will adjust the surface to agree with a 'telescope model' that allows for changes of the surface figure as a function of elevation (due to gravitational deformations), and possibly temperature gradients across the back-up structure. For the highest accuracy, a closed-loop system is being implemented employing laser ranging, with continuous feed-back and adjustment of the surface, which will be tied in to the telescope pointing.

The intermediate-accuracy open-loop system will use the array of surface actuators to keep the telescope panels in accord with the detailed model of the surface. The displacement of each actuator will be measured using an associated Linear Variable Differential Transducer (LVDT), a device whose output is closely proportional to its linear displacement. As the highest possible accuracy is needed for the open-loop system to permit its use not only at the lower frequencies, but generally as a back-up for the closed-loop system, many available models of LVDT have been intercompared to select to best-available design. Following this, the selected production LVDTs have been checked to measure the characteristics and internal consistencies of the units, and to evaluate the incidence of substandard examples.

Following an evaluation of seven designs of LVDT for use on the primary GBT reflecting surface (Schiebel, Vance and Salter, Oct 1991), it was decided to adopt the model marketed by Shaevitz. Over the past few months, as the units have been delivered, some 500 of the total of 2000 LVDT units have been tested in the same rig as was used for the inter-model tests. The characteristics of these units have been evaluated, and in particular the variations of these characteristics from unit to unit have been examined.

As the previous report (Schiebel, Vance and Salter, Oct 1991) had very limited circu-

lation, and as the methods on which the present evaluations are based were described in detail in that report, the technical part of that document is reproduced here.

2 The Equipment

In order to evaluate how a sample of LVDTs perform as a function of temperature and position, a system is needed that can both control the ambient temperature, and the position of a moving table to an accuracy better than is measurable by an LVDT. It was decided that the system designed for the present series of tests should be computer controlled, with the data being stored on floppy disk for subsequent analysis.

2.1 Linear Positioner

The linear positioner consists of a ball screw, attached to a movable table and driven by a DC motor. The movable table was constructed in the Green Bank Machine Shop, and was equipped to hold six LVDTs, although the electronics were adapted better to measuring five at a time.

A linear encoder is attached to the table to give a position readout that can be read by the computer. The linear encoder was purchased from Farrand Controls, has a resolution of 0.0001 inch, and can work over the temperature range required for the tests. This encoder operates on the same principle as the Inductosyns used to position the 140-foot telescope and the Green Bank interferometer, meaning that much experience is available in-house with this type of device. With this system, the table can be positioned with an accuracy of ten times better than an LVDT can measure.

2.2 Temperature Chamber

The second requirement was the ability to control the temperature of the LVDT from $\approx -18°$ to $+32°$ C. The size of the linear positioner decreed a test chamber of about $26 \times 36 \times 20$ inch. The cheapest commercial unit costs around \$3000 for a chamber requiring CO_2, which is difficult to handle. For the present application, it seemed best to buy a commercial chest-type freezer and modify this as necessary.

A 15.8 cu.ft. freezer was purchased and modified so that its temperature could be

controlled by computer. This modification was a matter of replacing the freezer thermostat with a solid-state relay, controlled by electronics of our own design. In addition, two fans and a heater were installed inside the freezer allowing its temperature to be raised under computer control.

2.3 LVDT Testing

The software to control the whole test fixture required the most effort. With the present system, it is possible to set the temperature of the freezer, and move the linear positioner, over any desired range. The data is recorded on floppy disk.

Groups of five LVDTs are tested at a time, at five different temperatures of $-15°$, $-3.9°$, $7.2°$, $18.3°$ and $29.4°$ C. At each setting, the freezer stays within $\approx$ 1° C of the demanded temperature. In the tests of the production units, the positioner was moved from +1.1 to −1.1 inch at each temperature, in increments of 0.1 inch. This was repeated three times and the data recorded as one file for each LVDT. Each file contained position as set by the linear encoder, and the raw A/D counts for that position. In addition, the temperature for each position was written to a separate file. All data were recorded in ASCII so that they could be read by most computers. Some groups of LVDTs were re-installed at a later date to check repeatability.

In the earlier tests, different LVDT signal-conditioning electronics and two cable lengths of 15 and 200 feet were also checked. No significant differences were found between the results for the two different cable lengths.

3 The Basic Data Processing

For each LVDT, the counts at 7.2° C were calibrated against the linear encoder readings via a least-squares best-fit analysis. Using the calibrated LVDT readings, the deviations for each LVDT unit, D = (LVDT − Encoder), were plotted against the position of the moving table for each of the five temperatures. (See Figs. 1a and b, which are examples for different two LVDT models taken from the earlier intercomparisons. The deviations at each temperature are plotted as connected lines, with different symbols representing different temperatures, as identified by the key at the bottom. The axes are marked in inches.) Figs. 1a and b show that the deviations from linearity are a function of both position and temperature. In the earlier tests, the variation of deviations with position and temperature varied greatly from one make of LVDT to another, and the Shaevitz model was selected largely because of its comparative invariance to temperature changes. For the Shaevitz units that will be used on the

GBT, the deviations for essentially all units tested followed a broad 'S' pattern as a function of position. A typical example is presented in Fig. 2.

4 Correction of the Apparent LVDT Readings to True Values

The problem posed by these tests was whether any simple expression could be found that would quantify the temperature behavior of D(x,T). The properties of a number of the LVDT models tested initially did indeed seem to offer a simple way of correcting the apparent distances derived from the LVDT readings to give improved estimates of the true distances. It was noticed that for any given LVDT, the response curves were basically similar at different temperatures, and both for the present Shaevitz sample and a majority of the other models previously tested, only the slope of the curves seemed to differ (see Figs. 1a and b, and 2). To investigate this behavior, the 7.2° C curve for each particular LVDT was taken as a standard, and this was subtracted from the responses for that device at the other four temperatures, leaving a set of residuals. For four of the seven LVDT models tested initially, including that from Shaevitz, this resulted in a set of straight lines whose slopes varied with temperature but whose intercepts on the x-axis were to first approximation temperature-independent (Fig. 3a and b; Fig. 3a corresponds to the unit whose response is shown in Fig. 1a, and is NOT a Shaevitz LVDT, while Fig 3b is for the Shaevitz production unit shown in Fig. 2.)

In all cases, the slopes of the best-fit lines to these residuals had a linear dependence on temperature. Thus, if T_o is taken as a standard temperature, then to good approximation for many types of LVDT, including Shaevitz, at any other temperature, T,

$$D(x,T) - D(x,T_o) = m(T)(x - x_o) \tag{1}$$

(i.e. the deviations from $D(x,T_o)$ at a given temperature T are a linear function of x, and these deviations are zero at a particular distance x_o. In the present case, T_o = 7.2° C was adopted.)

Further, for such LVDTs, m(T) appears to be a linear function of temperature. A typical example from plotting m(T) against T for a single LVDT is shown in Fig. 4. The circles represent the experimentally determined slopes (the slope at T_o = 7.2° C is zero by definition), and the best-fit line is also shown. Thus,

$$m(T) = n(T - T_o) \tag{2}$$

where n is a constant, equal to the slope of the slopes versus temperature.

Substituting (2) into (1),

$$D(x,T) = D(x,T_o) + n(T - T_o)(x - x_o) \tag{3}$$

for an LVDT having the above properties. Thus, the LVDT correction term D(x,T) can be predicted simply for any value of x and T, using a standard calibration at T_o, and a knowledge of n and x_o.

An alternative way of writing eqn (3) is,

$$D(x,T) = D(x,T_o) + (T - T_o)(nx + k) \tag{4}$$

where $k = -n \times x_o$, gives the change in offset at $x = 0$ per °C.

For each LVDT unit tested, values of n and k have been computed from (4).

5 The Results

A statistical summary of the characteristics of the Shaevitz LVDT units is presented in Table 1. The table lists the mean and rms of the values of n and k as a function of "station" in the test rig. The columns in the table represent,

a) Station number.

b) Number of units tested in that station.

c) Mean of n and its standard error (in thou/inch/° C).

d) Standard deviation of n (in thou/inch/° C).

e) Mean of k and its standard error (in thou/° C).

f) Standard deviation of k (in thou/° C).

The distributions of n and k for each station are shown graphically in Figs 5a and b. (Note that the units in Figs. 5 and 6 involve raw counts which should be divided by 30.3 to bring them into thou. Note also that the scale on the x-axis is different for each of the distributions of Fig 5b.) Both quantities vary with station position, which clearly cannot be a property of the LVDTs, but of the measuring rig. The variation of the mean values of n with station across the rig is not systematic. However, the mean values of n measured in the present tests are lower for all stations than for the Shaevitz units (or any other model) tested in the earlier experiment. The rms values are also lower than those found in the earlier tests, due to considering each station separately here. This means that in terms of temperature variations, the Shaevitz production units are somewhat less temperature sensitive EVEN than the test samples provided for evaluation, and have at least as close tolerances ! Only 2 units out of 483 (0.4 %) were too far out of tolerance to be represented on Fig 5a.

The distribution of k also has a strong dependence on station, with a systematic shift across the rig, as shown in Fig. 6. In the earlier tests of the different LVDT models, a similar systematic trend with station was found. All models were zero-adjusted at room temperature ($\approx$ 24° C) and $x = 0$ inch, and the earlier interpretation of this trend as a property of the test rig seems confirmed.

In view of the similar 'S-shape' appearance of the residuals for all units of the production model of LVDT's, and the smooth, broad nature of this curve, it was decided to see if a good approximation to the value of $D(x, T_o)$ for individual units could be obtained via the average curve for all units. Consequently, an average curve was built up as the tests progressed (Fig. 7) and subtracted from the measured $D(x, T_o)$'s for a random sample of 77 units. The rms deviations were computed for both the original distributions of $D(x, T_o)$, and the resultant curves following subtraction of the average distribution. The results are tabulated in Table 2, and presented as histograms in Fig. 8. Fig. 8 gives the distribution of rms's for both the uncorrected and corrected values of $D(x, T_o)$, plus the ratio of the corrected/uncorrected rms values. It is seen that the magnitude of the residuals, $D(x, T_o)$, is reduced, typically by a factor of greater than two. For only 2 of the 77 units did the corrected distributions have their rms's very marginally increased by the procedure (by less than 10 %). This would seem to offer a promising approach to reducing the overall residuals for surface setting with this model of LVDT.

6 Discussion

In respect of using the production LVDTs on the GBT, the following question was posed.

6.1 How well would the chosen model of LVDT set the GBT surface without temperature correction of its response ?

This essentially asks what quantifies the major differences between the LVDT and the linear encoder readings ? Among the most important parameters are,

- The deviations of an LVDT from the linear encoder at the standard temperature of 7.2° C is an intrinsic divergence from linearity. From Table 2 it is seen that the r.m.s. deviation is about 3.6 thou (90 μm) for the basic deviations, though this was reduced to 1.6 thou (40 μm) following correction by subtraction of the average distribution, as described above.

- The intrinsic temperature dependence of the LVDTs can be quantified from the results of the present tests. The deviations due to the temperature-dependence of the slope of the residual response, n, at temperature T will be $(T - T_o) \times n \times x$, and for $(T - T_o) = 22°C$, the extreme temperature deviation considered in the tests, and a movement of ± 1 inch, the deviations for the typical unit would be 0.8 thou (20 μm), peak-to-peak. (Note from Section 4 that there may well be a contribution to the estimated value of n from the measuring rig itself.) If the rms spread in the values of n, is σ_n, and the ambient temperature is 22°C different from the standard temperature, T_o, then for a movement of ± 1 inch, the maximum error is $\Delta D = (T - T_o) * \sigma_n * 2$. This yields, $\Delta D = 0.4$ thou (10 μm).

  The offset constant k introduces an additive constant for any given temperature, which thus would not affect surface setting for a uniform temperature distribution. However, the spread of k values would introduce an error. If the rms spread is σ_k, then the rms error would be $(T - T_o) * \sigma_k$. For the production LVDT model, this would yield an r.m.s. error of 0.35 thou (9 μm) for a 22° C difference from T_o.

- If there is a temperature differential across the dish, then the offset k will produce an error of $\Delta T * k$. If $\Delta T = 2°C$, a maximum error of about 0.35 thou (9 μm) would result. However, it should be noted that much of the contribution to the measured value of k may be in the measuring rig (see Section 4).

  Similarly, for such a temperature differential, the slope of slopes, n, would produce a maximum error of $\Delta T * n * 2$ for a movement of ± 1 inch. For the present LVDT units, and a 2° C temperature differential, this equals 0.08 thou (2 μm).

The above values suggest that a measurement rms of about 2 thou (50 μm) should be possible without temperature correction, provided allowance is made for the average deviations of the LVDTs from a fully-linear response. Without this correction, a figure of 4 thou (100 μm) would be appropriate. The Shaevitz design seems to be rather temperature invariant, and the measured temperature effects represent only second-order terms.

7 Concluding Remarks

A large sample of the LVDTs selected for use in the surface-setting system of the GBT have been evaluated using a test rig developed 'in-house'. The characteristics of the devices in terms of temperature and position differences have been measured. Consideration of the use of these devices for setting the telescope panels suggests that a setting accuracy of 4 thou (100 μm), and perhaps 2 thou (50 μm) with a simple correction, should be possible even without any consideration of the temperature-dependent characteristics of the units.

Table 1: **Statistics of the Tests.**

Station	No. tested	*Mean of n & st. error* (thou/inch/°C)	*RMS of n*	*Mean of k & st. error* (thou/°C)	*RMS of k*
1	96	0.0143 ± 0.0011	0.0109	−0.2366 ± 0.0015	0.0142
2	96	0.0153 ± 0.0009	0.0086	−0.1913 ± 0.0018	0.0178
3	97	0.0326 ± 0.0009	0.0088	−0.1693 ± 0.0017	0.0163
4	98	0.0119 ± 0.0009	0.0086	−0.1312 ± 0.0016	0.0160
5	96	0.0213 ± 0.0007	0.0073	−0.0863 ± 0.0015	0.0150

Table 2: **RMS Deviations at 7.2°C.**

	Number	*Mean of RMS's & st. error*	*RMS of RMS's*
Uncorrected Data	77	3.58 ± 0.10 thou	0.85 thou
Corrected Data	77	1.58 ± 0.08 thou	0.68 thou
Corrected/Uncorrected	77	0.46 ± 0.02	0.20

Fig 1a

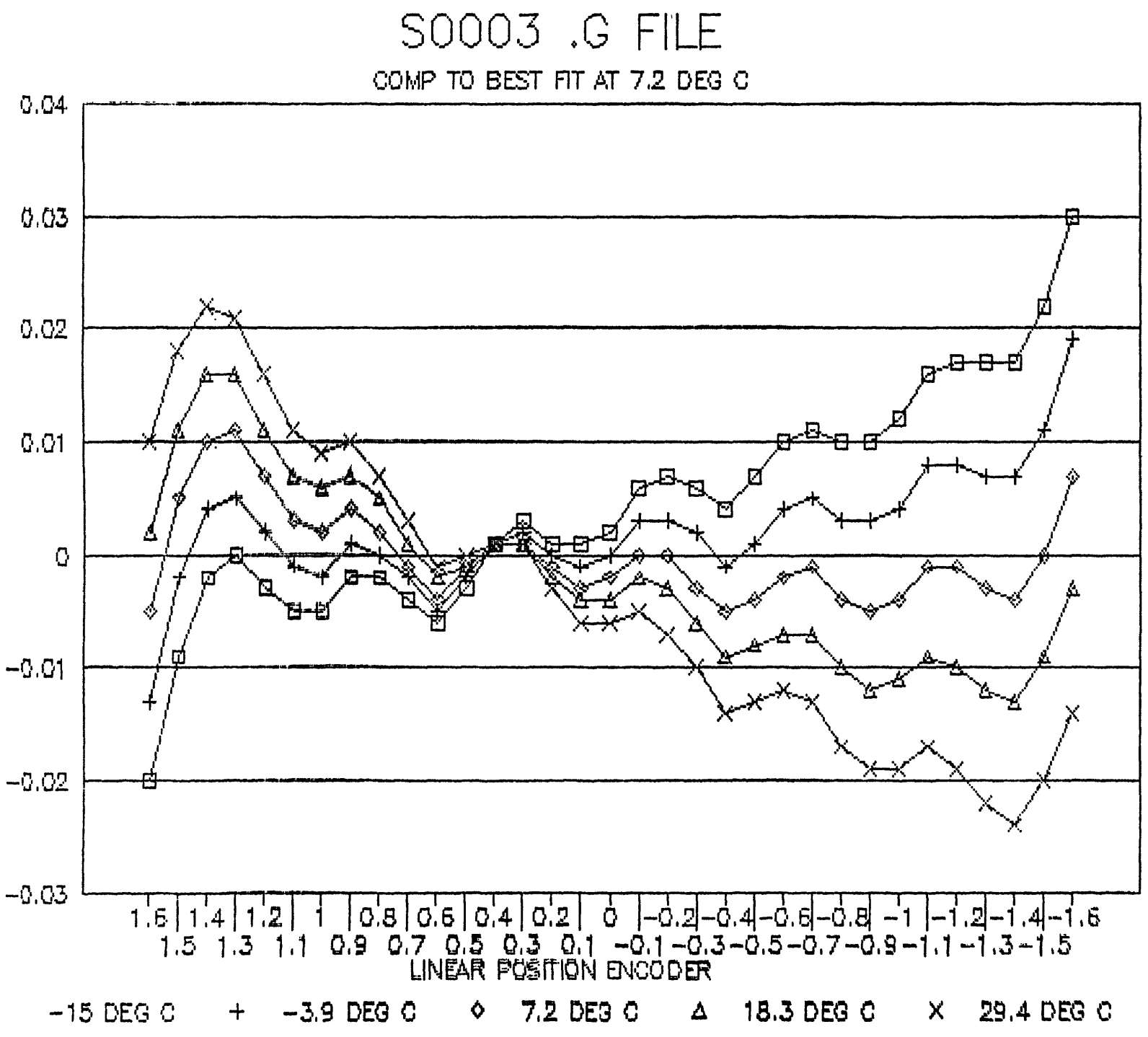

S0003 .G FILE
COMP TO BEST FIT AT 7.2 DEG C
0.04
0.03
0.02
0.01
0
-0.01
-0.02
-0.03
Y MEAS - Y IDEAL
1.6 1.4 1.2 1 0.8 0.6 0.4 0.2 0 -0.2 -0.4 -0.6 -0.8 -1 -1.2 -1.4 -1.6
1.5 1.3 1.1 0.9 0.7 0.5 0.3 0.1 -0.1 -0.3 -0.5 -0.7 -0.9 -1.1 -1.3 -1.5
LINEAR POSITION ENCODER
-15 DEG C
-3.9 DEG C
7.2 DEG C
18.3 DEG C
29.4 DEG C

Fig. 1b

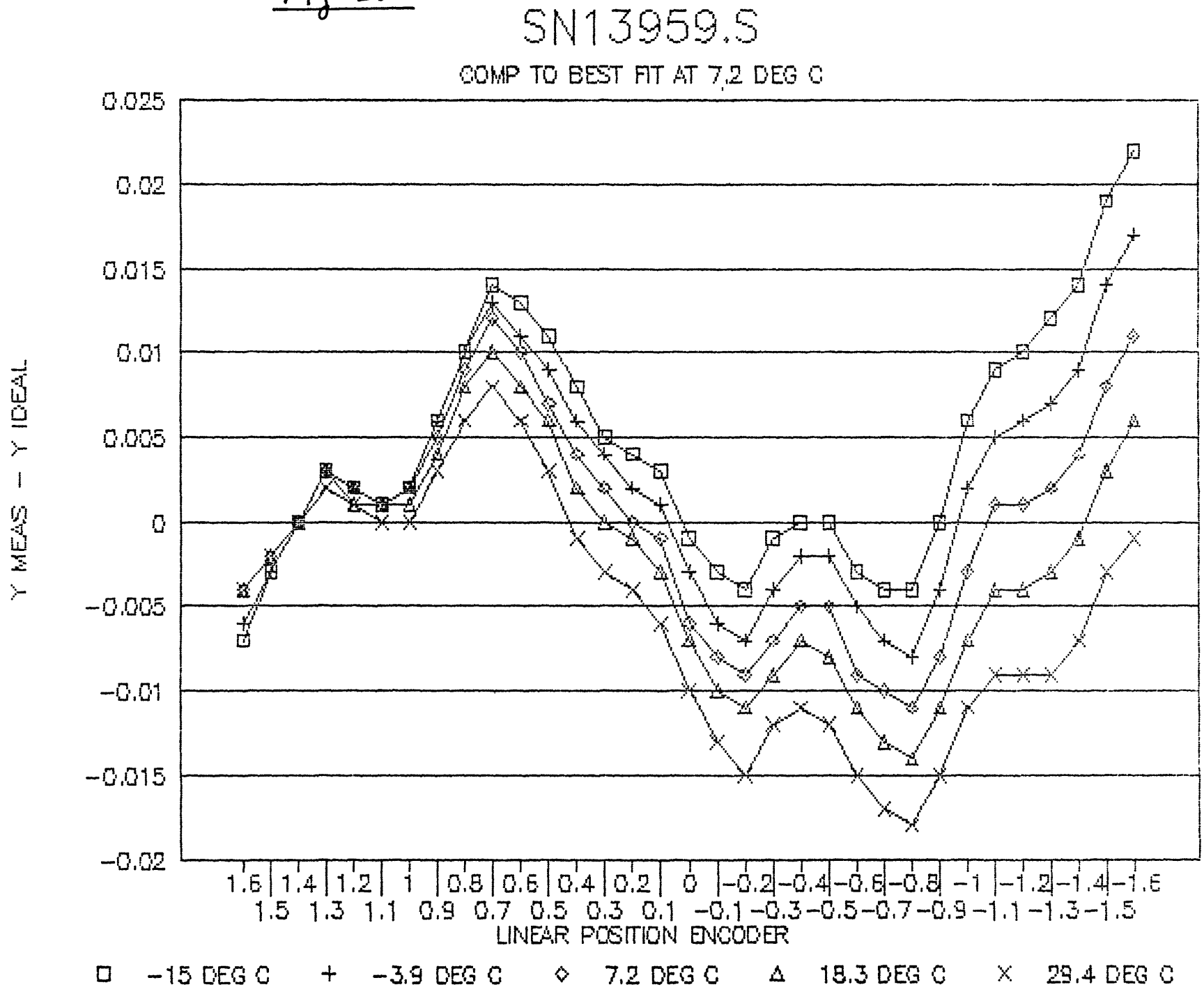

SN13959.S
COMP TO BEST FIT AT 7.2 DEG C
Y MEAS - Y IDEAL
0.025
0.02
0.015
0.01
0.005
0
-0.005
-0.01
-0.015
-0.02
1.6 1.4 1.2 1 0.8 0.6 0.4 0.2 0 -0.2 -0.4 -0.6 -0.8 -1 -1.2 -1.4 -1.6
1.5 1.3 1.1 0.9 0.7 0.5 0.3 0.1 -0.1 -0.3 -0.5 -0.7 -0.9 -1.1 -1.3 -1.5
LINEAR POSITION ENCODER
-15 DEG C
-3.9 DEG C
7.2 DEG C
18.3 DEG C
29.4 DEG C

Fig. 2

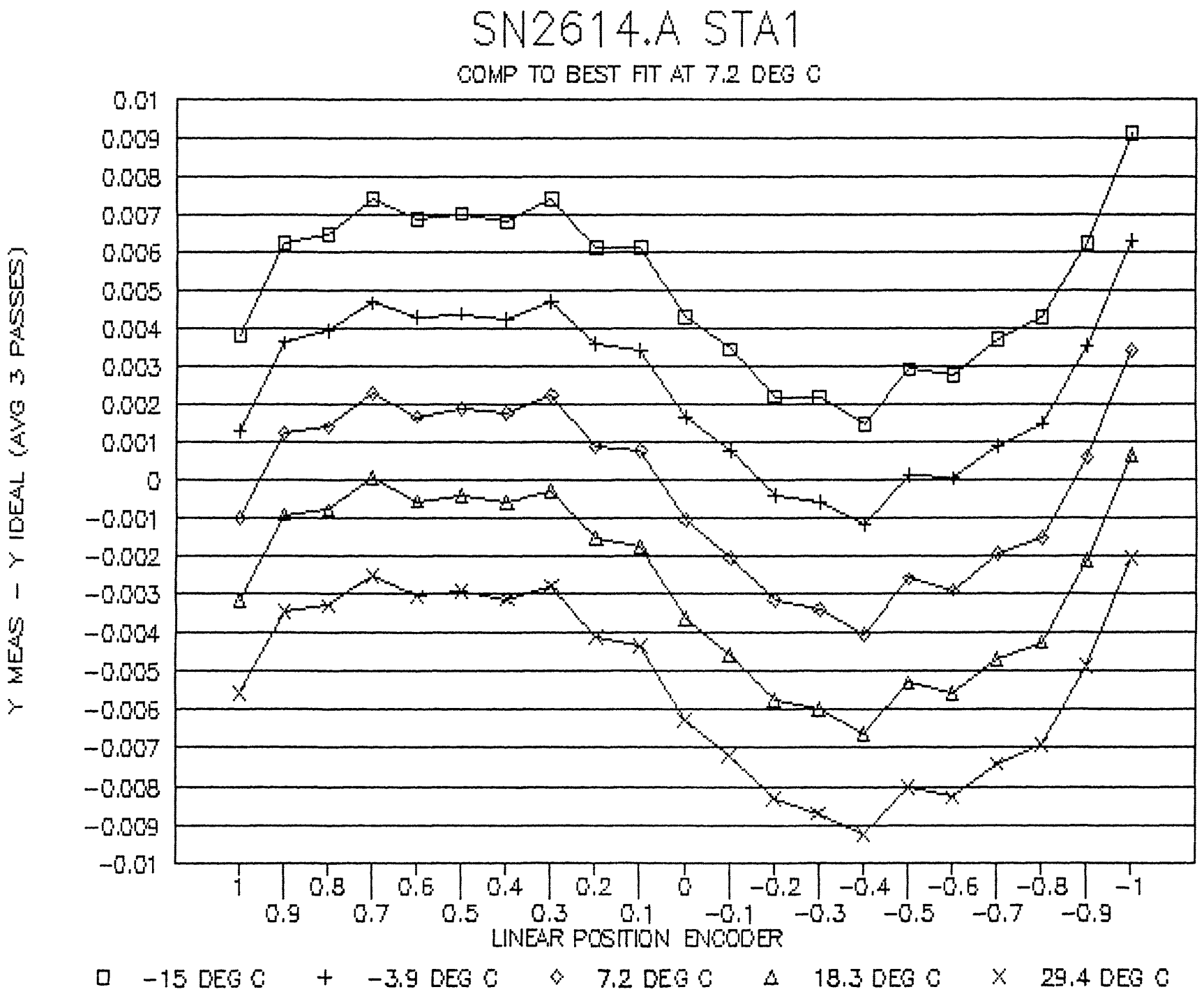

SN2614.A STA1
COMP TO BEST FIT AT 7.2 DEG C
Y MEAS - Y IDEAL (AVG 3 PASSES)
0.01
0.009
0.008
0.007
0.006
0.005
0.004
0.003
0.002
0.001
0
-0.001
-0.002
-0.003
-0.004
-0.005
-0.006
-0.007
-0.008
-0.009
-0.01
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
-0.4
-0.5
-0.6
-0.7
-0.8
-0.9
-1
LINEAR POSITION ENCODER
-15 DEG C
-3.9 DEG C
7.2 DEG C
18.3 DEG C
29.4 DEG C

Fig 3a

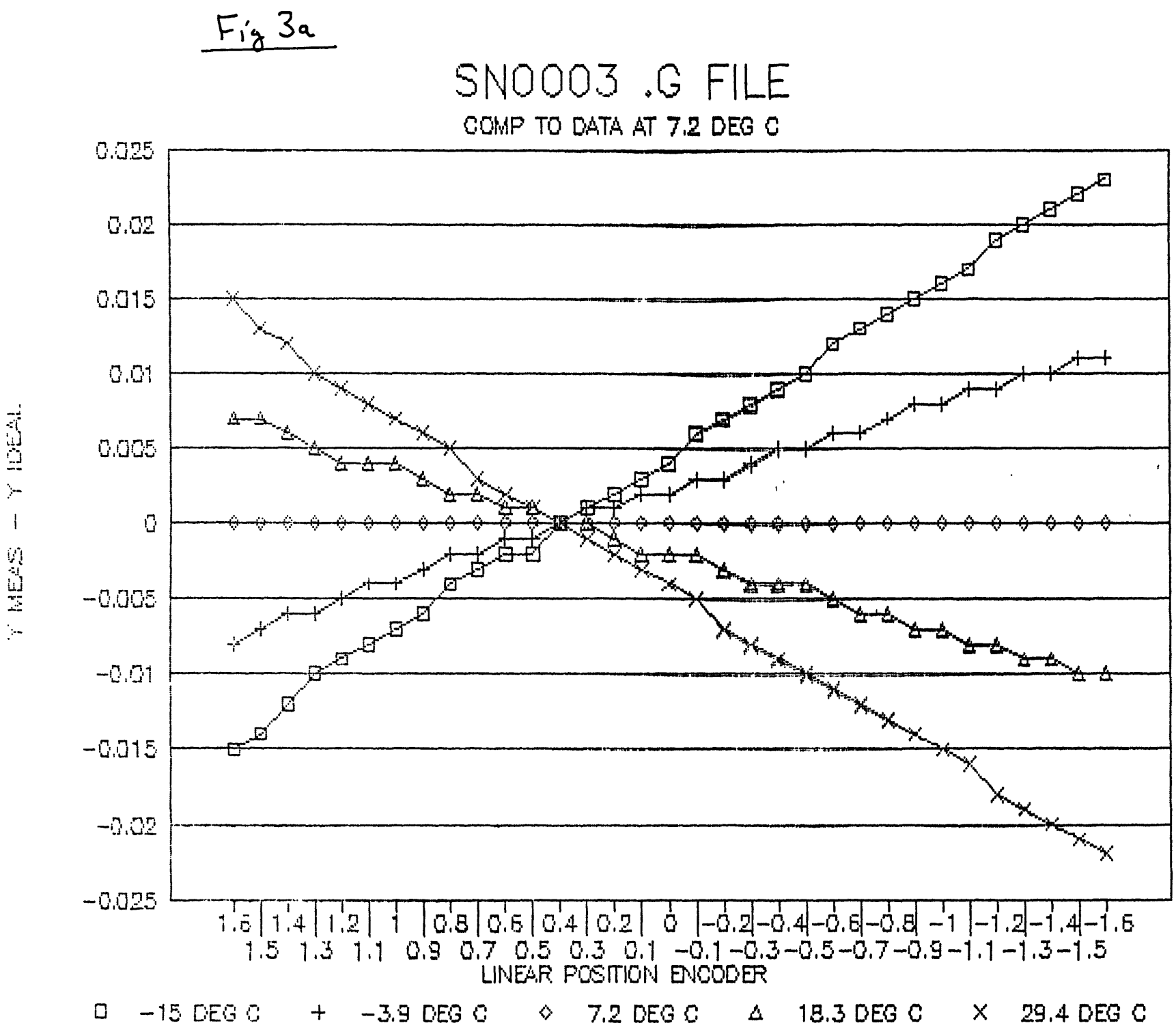
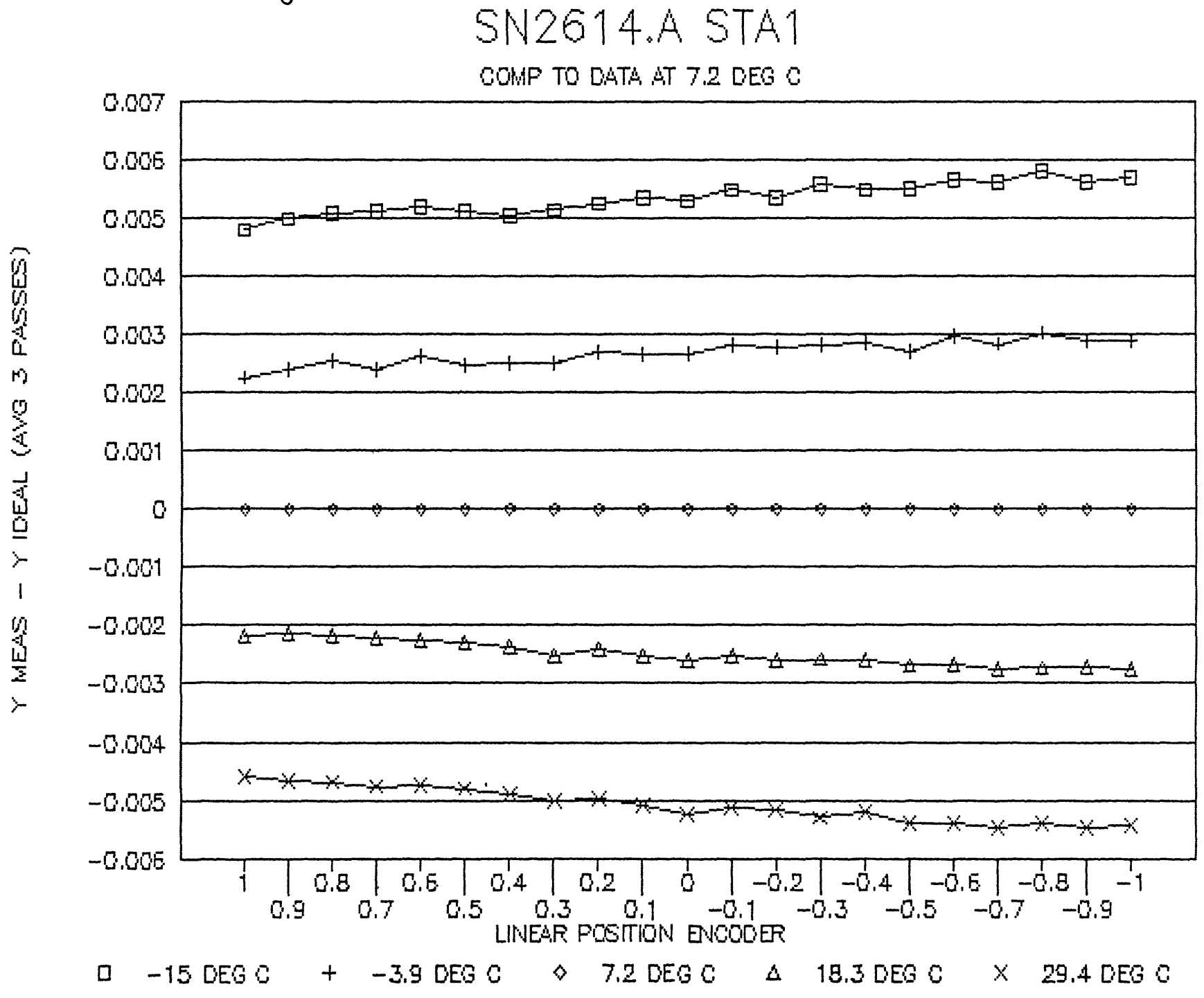

SN0003 .G FILE
COMP TO DATA AT 7.2 DEG C
Y MEAS - Y IDEAL
0.025
0.02
0.015
0.01
0.005
0
-0.005
-0.01
-0.015
-0.02
-0.025
1.6 1.4 1.2 1 0.8 0.6 0.4 0.2 0 -0.2 -0.4 -0.6 -0.8 -1 -1.2 -1.4 -1.6
1.5 1.3 1.1 0.9 0.7 0.5 0.3 0.1 -0.1 -0.3 -0.5 -0.7 -0.9 -1.1 -1.3 -1.5
LINEAR POSITION ENCODER
□ -15 DEG C + -3.9 DEG C ◇ 7.2 DEG C △ 18.3 DEG C × 29.4 DEG C

Fig 3b


SN2614.A STA1
COMP TO DATA AT 7.2 DEG C
Y MEAS - Y IDEAL (AVG 3 PASSES)
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
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
-0.4
-0.5
-0.6
-0.7
-0.8
-0.9
-1
LINEAR POSITION ENCODER
-15 DEG C
-3.9 DEG C
7.2 DEG C
18.3 DEG C
29.4 DEG C

Slope (Counts/Inch)

LVDT : SN0003.G

Fig 4

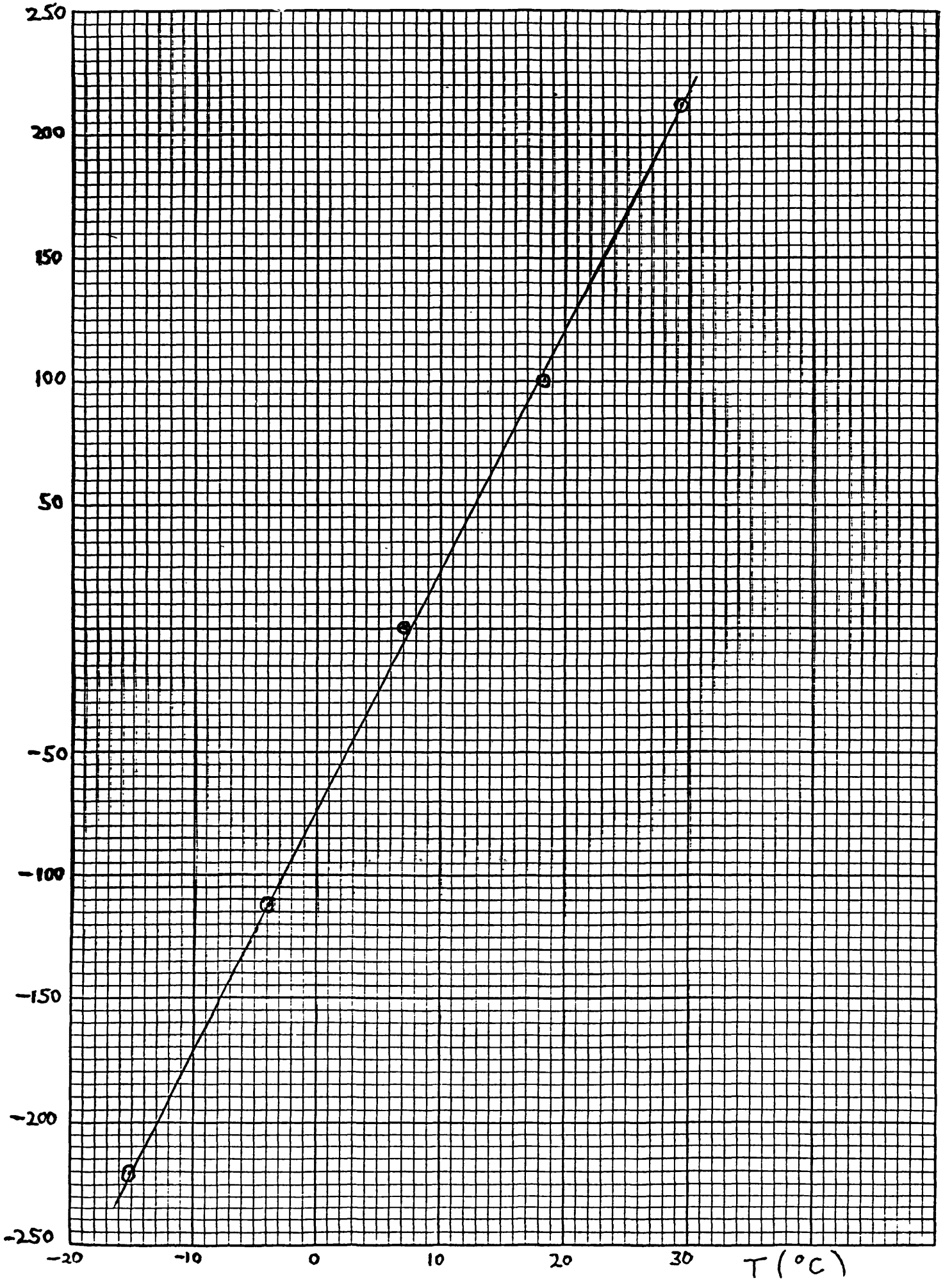
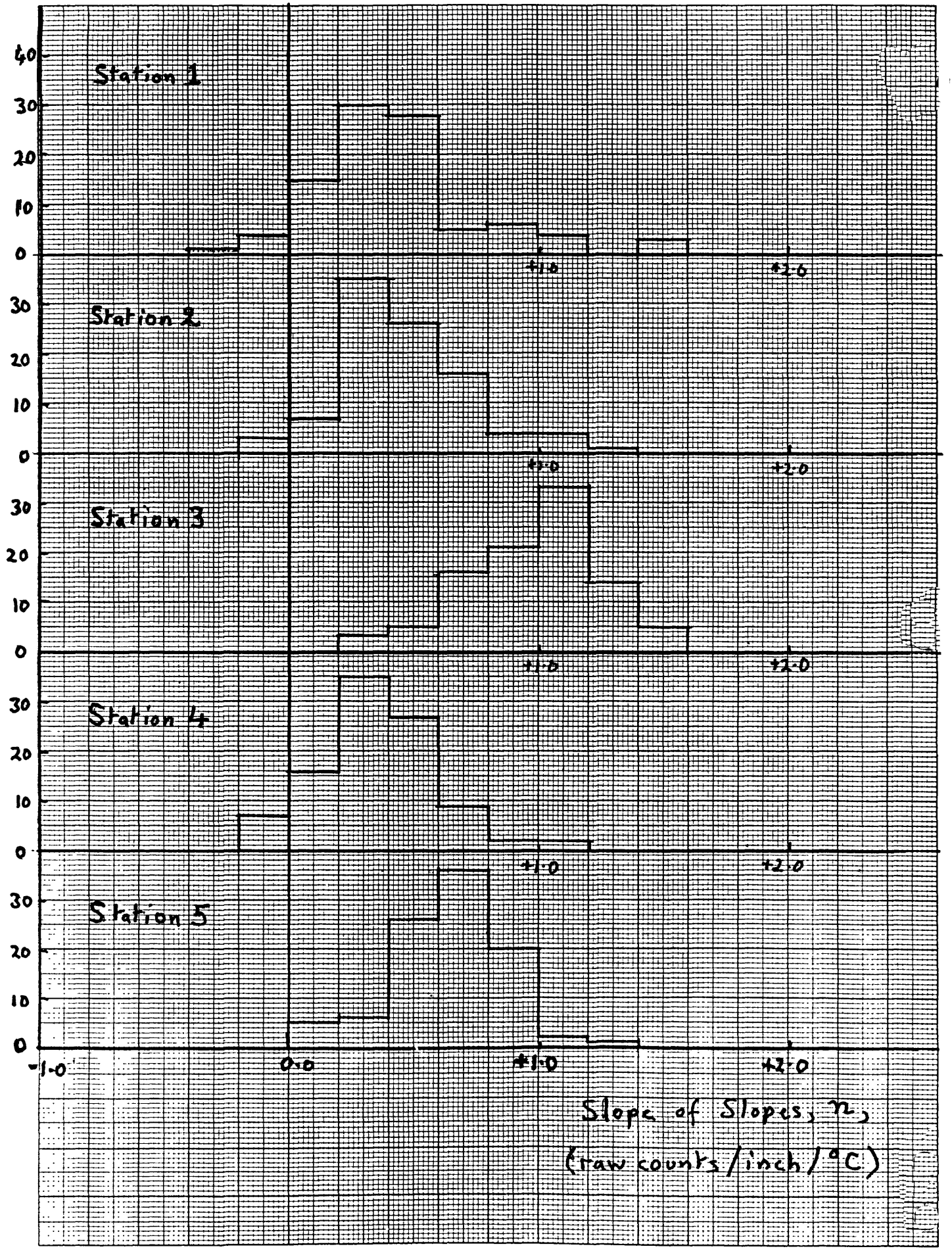
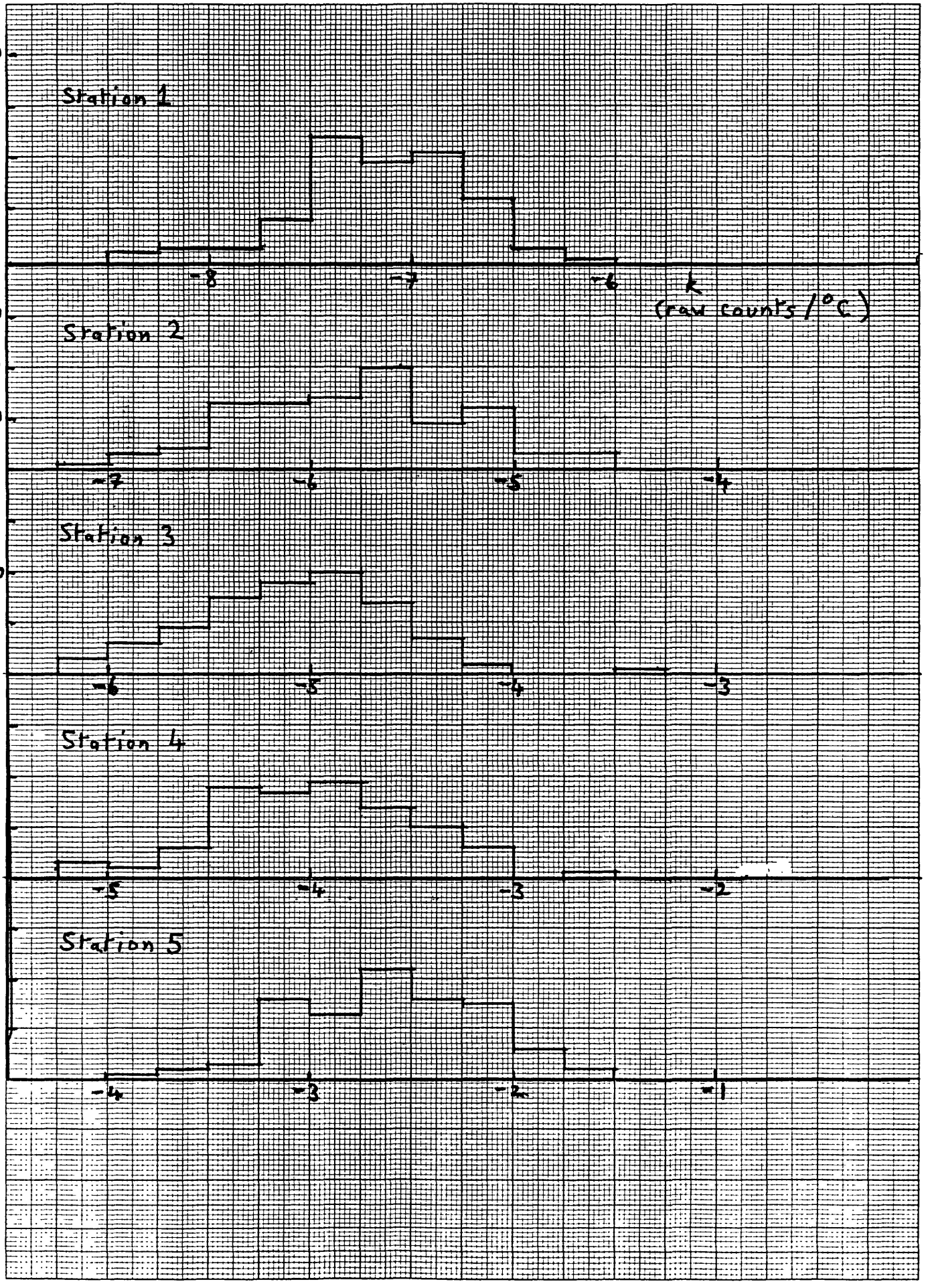


Fig 5a



46 1510
K+E 10 X 10 TO THE CENTIMETER 18 X 25 CM.
KEUFFEL & ESSER CO. MADE IN U.S.A.

Fig 5b



46 1510
10 X 10 TO THE CENTIMETER 18 X 25 CM.
KEUFFEL & ESSER CO. MADE IN U.S.A.

Fig 6

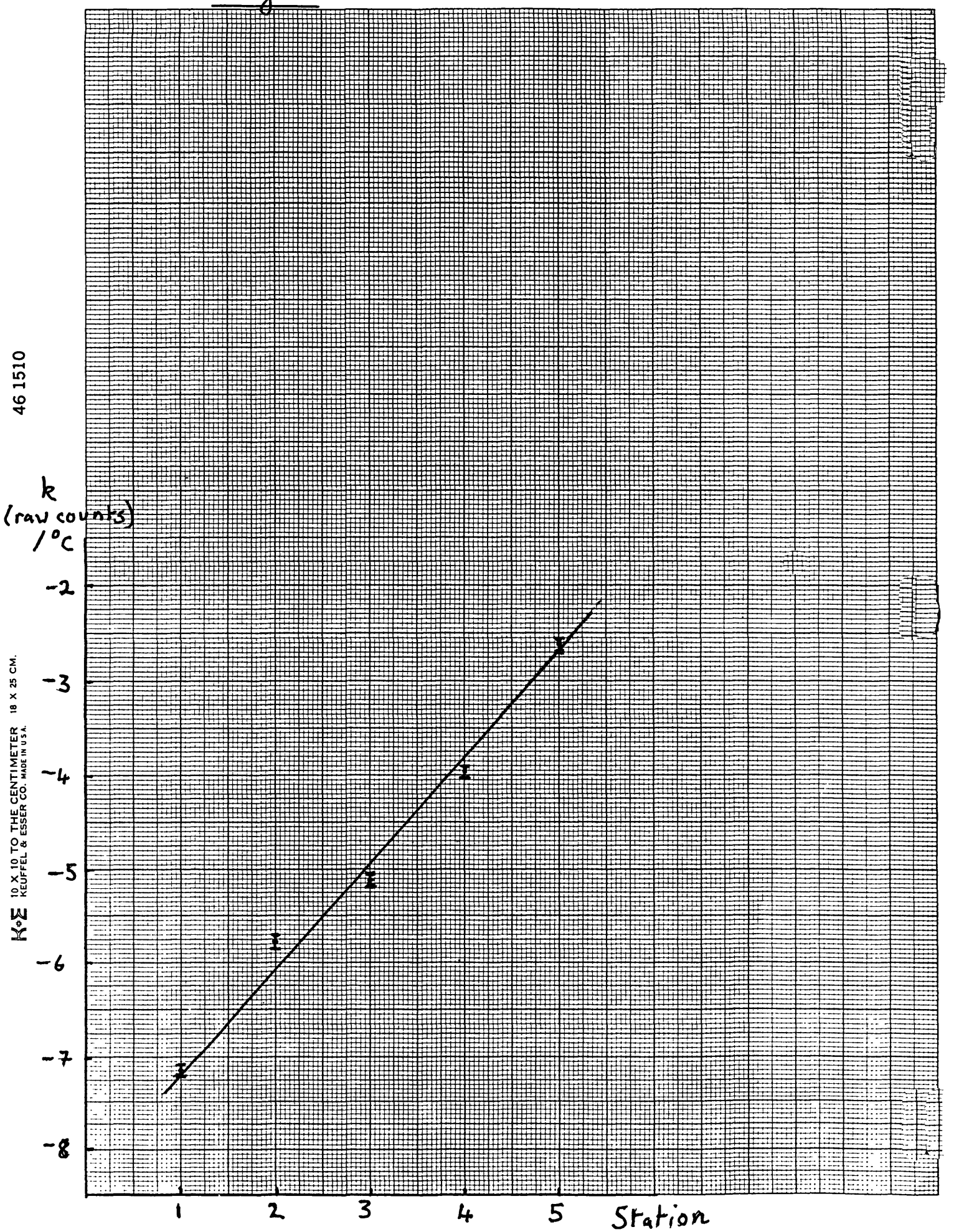

k
(raw counts)
/°C
-2
-3
-4
-5
-6
-7
-8
1
2
3
4
5
Station
46 1510
10 X 10 TO THE CENTIMETER 18 X 25 CM.
KEUFFEL & ESSER CO. MADE IN U.S.A.

Fig. 7

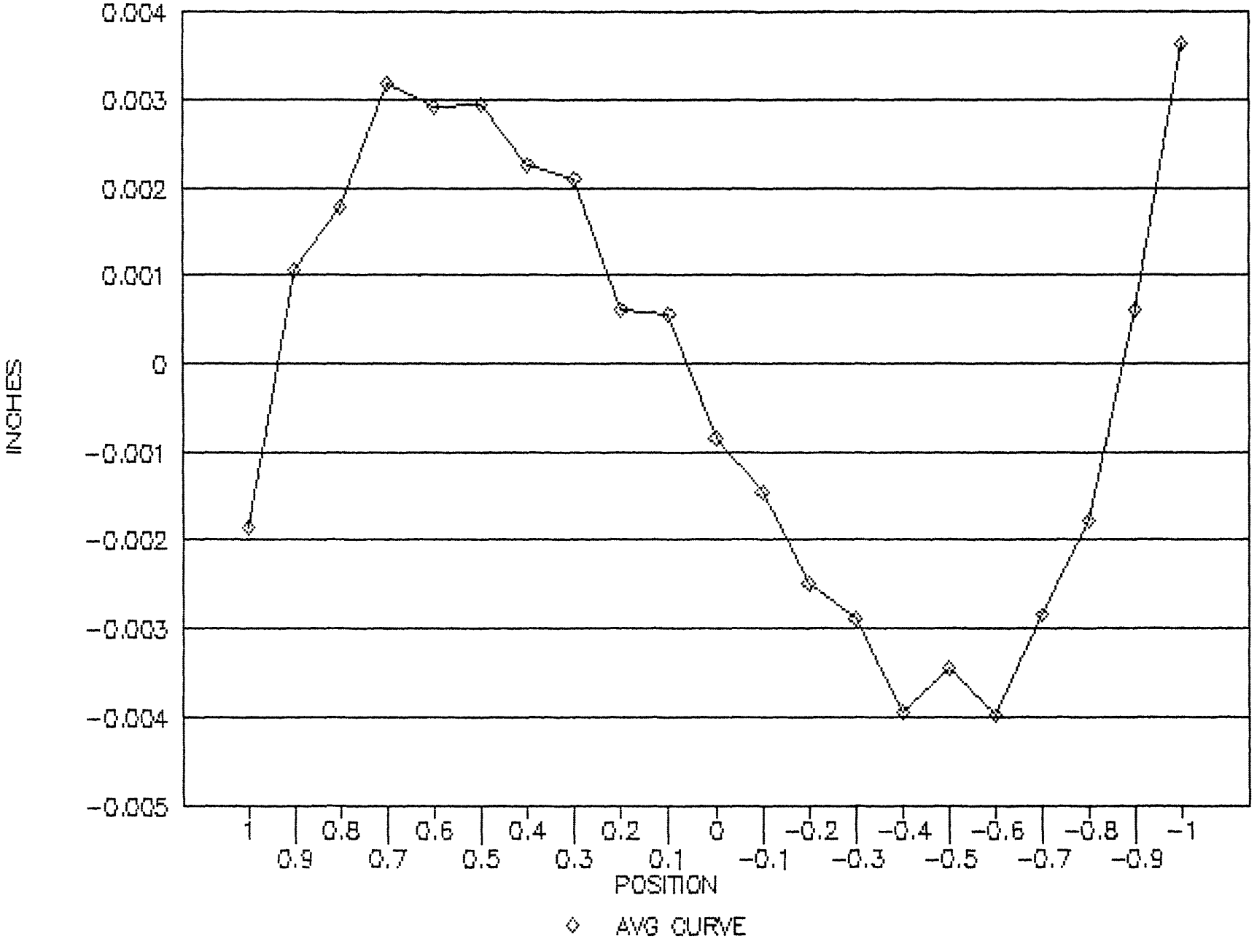
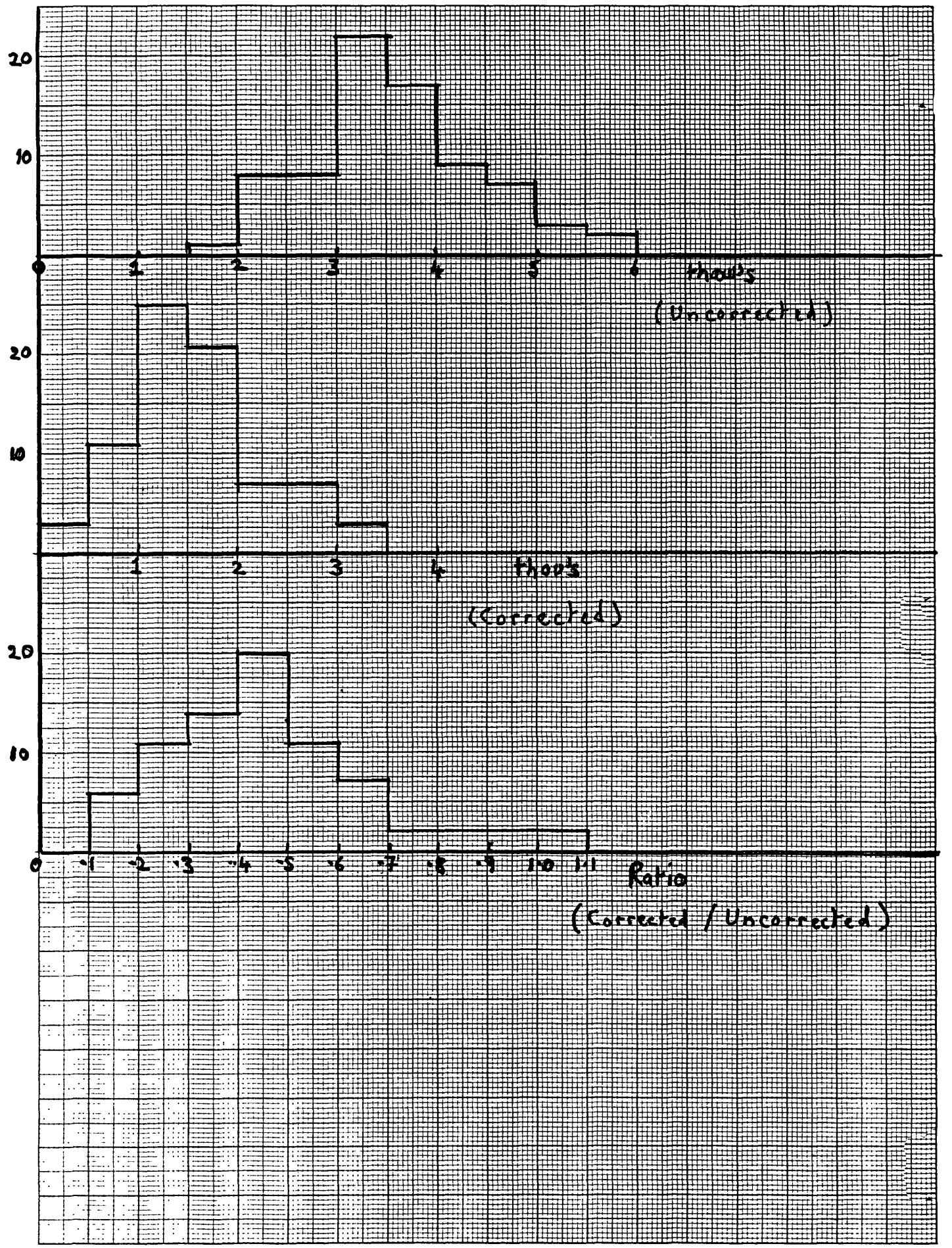

0.004
0.003
0.002
0.001
0
-0.001
-0.002
-0.003
-0.004
-0.005
INCHES
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
-0.4
-0.5
-0.6
-0.7
-0.8
-0.9
-1
POSITION
AVG CURVE

Fig. 8



46 1510
10 X 10 TO THE CENTIMETER 18 X 25 CM
KEUFFEL & ESSER CO. MADE IN U.S.A.