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THERMAL DEFORMATIONS OF THE 140-FT BUILDING

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Summary

During 98 days, angular tilts at five locations were measured with three electronic levels; the ambient air temperature was recorded, and wall temperatures at nine locations were measured with three to five thermistors. The peak-to-peak range of EW tilts was only 9 arcsec, but 51 arcsec for the NS tilts, during ambient air changes of 47°C ptp.

A simplified thermal model of the building explains the observed deformations within 17% rms error. The main effect is a strong thermal warp of the deck-passage system (ends down for warmer air), resulting from the different degree of exposure to ambient air for its upper and lower surface. Second, the central bearing tower walls are expanding for warmer air, causing a parabolic deformation of the ceiling. Third, the temperature inside some rooms is not regulated by thermostats, and an average tilt of the building (15 arcsec ptp) is found to be correlated with these varying temperatures.

Some improvements are suggested. First, all lower parts of the deck, from the south end to the beginning of the brake casting on the north deck, should be filled out with pads, consisting of electric heat coils with thermostats on the bottom, then 3 inches of insulating isofoam sprayed on, and topped with 3 inches of concrete wearing course. Second, the tower walls should be sprayed with a 1/2 inch layer of isofoam. Third, the internal air regulation should have two more thermostats. With these changes, our thermal model predicts an improvement of 76% rms for the various single deformations, and a resulting polar shaft tilt close to zero.

A more reliable but more expensive alternative (replacing the first two items) would be to spray the whole building, from ground level including passages and deck up to the tower top, with a thick layer (3 inch) of isofoam. This brings all thermal deformations close enough to zero, and does not depend on the validity of our thermal model. For a decision, we need better cost estimates than we have at present.

Introduction

The first plans for improving the 140-ft telescope started in 1974. Regarding the surface deformation during tilt, we found a strong gravitational astigmatism which can be corrected by a deformable subreflector (von Hoerner and Wong, 1975); and a mathematical method for deriving correcting subreflector surfaces, for any given primary surface, was developed (von Hoerner, 1976). The actual design of a deformable subreflector is presently being worked on by W. Y. Wong.

Improving the surface performance is meaningful only if the other performances are improved as well. First, an automatic focal length adjustment, elevation-dependent, was suggested and installed (von Hoerner, 1975a). Second, the pointing errors are much too large even for the present state of the surface; see Table 3. An investigation of the thermal pointing errors occurring between concrete deck and center of backup structure was described in detail (von Hoerner, 1975b), including refraction errors. It was found necessary to shield the polar axis and the long, slender yoke arms against solar radiation (and sky versus ground radiation at night), for example, by spraying on a 1.5 inch thick layer of styrofoam or some similar insulating material giving a thermal time constant of over 40 hours. Bill delGiudice is working out the details and is contacting firms.

The present report is concerned only with the thermal deformations of the 140-ft concrete building and their resulting pointing errors, and a method for improvement is suggested, since it turns out that the whole massive building, with three solid feet of wall thickness, deforms a lot more than anyone would have guessed; see Tables 1 and 3.

Instead of writing this again as an Electronics Division Internal Report, it was suggested to start a separate series of Engineering Division Internal Reports where all telescope investigations and improvements should be included.

I. Measured Thermal Deformations

1. Experimental Setup

Three electronic levels (pendulum-capacitor) and up to five thermistors (electric resistance thermometers) were mounted at various places at the 140-ft building as shown in Figure 1. Ambient air temperature was measured south of the building. Readings were taken by the telescope operators at regular intervals, between 2 and 8 times per day. Tables 1 and 2 give the observing periods and the observed peak-to-peak (ptp) ranges, together with the ptp range of ambient air temperature during the same period.

From December 19 to February 23, the operator noted also the degree of sky coverage, wind speed and direction, and precipitation. Since no obvious correlation with the level readings was found, this was interrupted.

Some more details about the building are given in Figure 2 and 3, showing the deck plan and tail bearing house and polar drive house, and two cross sections of the passages with their wide flanges.

TABLE 1

Electronic levels. Observing period, peak-to-peak ranges of observed tilts, and ptp temperature of ambient air during same period.

Level	Location	Direction	Observing Period			Tilt, ptp arc-sec	Ambient air, ptp °C
			From	To	Days		
A*	Main bearing	EW	Dec. 19	Jan. 9	21	9	25.2
B*	Main bearing	NS	Dec. 19	Jan. 15	27	12	25.2
C	Tail bearing	NS	Dec. 19	Mar. 26	98	42	47.1
A	South passage	NS	Jan. 9	Mar. 26	77	38	47.1
B	North passage	NS	Jan. 16	Mar. 26	70	51	
(A+B)/2	Passages, avg. tilt	NS	Jan. 16	Mar. 26	70	15	47.1
(A-B)/2	Passages, ends	Down	Jan. 16	Mar. 26	70	44	

TABLE 2

Thermistors. Peak-to-peak ranges (locations, see Figure 1).

Thermistor	Location, floor	Observing Period			Ptp Temperature Range (°C)	
		From	To	Days	Thermistor	Ambient air
1	Out, S, 1st	Feb. 1	Mar. 26	49	30.0	37.9
2	In, S, 1st				4.4	
3	In, N, 1st				5.1	
4	In, S, 2nd				5.7	
5	Out, N, 1st				23.2	
6	In, N, 2nd	Jan. 7	Feb. 4	19	3.3	33.2
7	Main bearing	Jan. 7	Jan. 15	8	1.7	23.6
8	In, S, 3rd	Jan. 15	Feb. 4	20	3.0	33.2
9	In, N, 3rd				3.2	

2. Main Bearing Deformations

The east-west tilt was observed during 21 days, six of which are shown in Figure 4. The most obvious deformation is a small wiggle caused by strong sunshine: before noon, the sun shines at the east side of building and tower, warming this side up and expanding it, which causes a tilt to the west; and the opposite occures after noon. This wiggle was observed on all six sunny days, with an average of

$$\text{Main bearing, EW wiggle} = 3.0 \text{ arcsec ptp.} \tag{1}$$

In addition, thre was a slow, small change of the average reading, amounting to

$$\text{Main bearing, EW average change} = 5.0 \text{ arcsec ptp,} \tag{2}$$

which could not be correlated to any temperature readings. In the present report, these EW movements shall be neglected, since they are small, cannot be prevented, but could be corrected for in the computer (using the level readings) if wanted.

The north-south tilt of the main bearing was observed during 27 days. A rather good correlation with the NS tilt of the tail bearing was found in Figure 5, with an rms scatter of only 1.7 arcsec for a range of 12 arcsec:

$$B^* = +0.61\ C \pm 1.7 \text{ arcsec rms.} \tag{3}$$

3. Tail Bearing and Passages

The tail bearing tilt was observed during the entire period of 98 days, but NS only. The total observed movement is 42 arcsec ptp. For obtaining a better understanding of these large deformations, levels A and B were removed at the main bearing and mounted in the passage ways; see Figure 1. It then turned out that A and C move very similar in parallel, while B moves in the opposite direction.

The main deformation of the building thus is a large bending or warp of passages and deck (ends of deck up for cold ambient air, and down for warm air), expressed as (A - B)/2. In addition, we have a smaller average tilt, expressed as (A + B)/2. Two time runs of these quantities are shown in Figures 6 and 7.

The internal correlations of the measured tilts are shown in Figures 8 for C versus A, and in Figure 9 for B versus A. The result is

$$C = +1.16\ A \pm 3.6 \text{ arcsec rms,} \tag{4}$$

$$B = -1.40\ A \pm 5.2 \text{ arcsec rms.} \tag{5}$$

In Table 3 we give a summary of all thermal deformations measured so far, including those of the polar mount structure as described previously (von Hoerner 1975b), and extrapolated to the ptp ranges expected for the whole year, between a cold winter night and a warm summer day.

TABLE 3

Summary of 140-ft Thermal Pointing Errors.
(All data given are peak-to-peak ranges.)

Description	Observations (days)	Errors (arcsec)		Ambient Air (°C)
		NS	EW	
1. *CONCRETE BUILDING*				
a. Total, measured				
At main bearing	27	12	9	25
At tail bearing	98	42	--	47
Resulting shaft tilt (estimated)	98	20	8	47
b. Single observations (NS)				
Bending both passage ways up	70	44	--	47
Average tilt of building		15	--	
2. *POLAR MOUNT STRUCTURE*				
a. Total error				
(measured above declination axis, minus console readings)	4	105	37	19
b. Single contributions				
Platform elongation (2.4 mm)	4	21	7	19
Polar shaft bending		35	12	
Yoke arms bending		70	16	
3. *WHOLE YEAR, ESTIMATED*				
a. As is, uncorrected				
Concrete building	365	40	20	60
Mount structure		115	45	
Total errors, RSS		122	49	
b. Residuals, if corrected (but not shielded)				
Concrete building (4 levels)	365	20	10	60
Mount structure (8 thermistors)		37	15	
Total residuals, RSS		42	18	

4. Correlation with Ambient Air Temperature

Figure 6 shows that the observed tilts of A, B, and C are well correlated with the air temperature, but are somewhat delayed and smoothed. In order to obtain the correlation between deformations and ambient air in a proper way, one should fold the air data with a theoretically derived delay function (which depends not only on the wall thickness and the thermal constants of concrete, but unfortunately also on the Fourier spectrum of the air data, since different periods give different delays and different amplitude decays).

Instead of all this, Figure 10 shows the raw data for level C, where all drastic temperature changes and 16 hours thereafter are omitted, where rising temperatures are marked as "+", falling ones as "X", and nearly constant periods as "o". A best-fitting straight line should now go through the open circles and should be below all X signs and above all + signs. This gives an unbiased estimator for the correlation coefficient, resulting in 1.06 arcsec/°C. The scatter of the open circles is ± 3.0 arcsec. Using equations (3), (4), and (5), we then obtain the thermal NS deformations of the building as:

south passage ...	A	=	−0.92 arcsec/°C	+ means tilting north for warmer air.	(6)
north passage ...	B	=	+1.28		(7)
tail bearing	C	=	−1.06		(8)
main bearing	B*	=	−0.65		(9)
average tilt	(A+B)/2	=	+0.18		(10)
deck warp	(A−B)/2	=	−1.10	+ means ends up for warmer air.	(11)

It seems now that this bending can be understood. For a certain intermediate part of the passageways (between the tower on top and the vertical building walls below), the floor of the passage is kept at constant room temperature, while the ceiling (platform) is exposed to ambient air. If the ambient air gets warmer, the platform expands and its ends bend down. This effect is further increased by the thick flanges of the platform ceiling (Figure 3) which are exposed to ambient air at both upper and lower sides. And the tower of the main bearing sits unsymmetrically on the platform (see Figure 4) following the movement of the south passage more than the counter-movement of the north passage, but being somewhat diminished by the latter. These considerations will lead to the thermal model of Section II.

As to the empirical delay between deformations and air temperature, we see from Figure 6 that sudden large changes of the air temperature (as the step-function on January 19) give first a deformation of small amplitude delayed only by 2-3 hours, but then a gradual increase with a 1/e-time of about one day. Furthermore, some rough trials with various smoothings and delays for all our data give a best fit with an average delay of about 12 hours:

$$\text{delay } \tau = \begin{cases} \text{12 hours, average of all data,} & (12) \\ \text{24 hours, long-term step-functions.} & (13) \end{cases}$$

5. <u>Theoretical Thermal Delay</u>

For short-term sinusoidal variations of the air temperature, one can show that the delay averaged over a thick wall is a phase shift of 45° (1/8 of the period), independent of material and wall thickness. The average delay of 12 hours, of equation (12), then should be explained as 1/8 of the period of the most dominant weather change, resulting in a 4-day period, which agrees well with the normal 4-day period claimed by the meteorologists (in winter, and 6 days in summer).

But for a long-lasting step-function of the air, as of January 19, wall thickness and material do matter, giving an exponential delay with

$$\tau = \frac{c\,\rho}{\pi^2 k} d^2 \qquad \left| \begin{array}{lll} c & = & \text{heat capacity} \\ k & = & \text{heat conductivity} \\ \rho & = & \text{density} \\ d & = & \text{wall thickness} \end{array} \right. \tag{14}$$

For d = 3 ft and concrete, we obtain, in good agreement with the rough empirical estimate of equation (13),

$$\tau = 25 \text{ hours.} \tag{15}$$

6. Miscellaneous

When the electronic levels were first installed, the graph recorder showed regular vibrations of 3 arcsec ptp and about 4 Hz, probably from pump motors in the building. Thus, an RC time constant of $\tau = 5$ sec was installed for smoothness. All measurements were taken this way.

Fast changes of the telescope pointing show up on the recorder as sudden jumps, but never more than 0.8 arcsec large. Thus, switching the telescope on-off source in total power yields a small regular wiggle.

Strong gusty winds show up on the graph as irregular wiggles, but again only small — about 2 arcsec ptp for gusts up to 40 mph.

On February 4, we observed the strong earthquake in Guatemala on all three levels as a distinct regular wiggle of 2.2 arcsec ptp, seven minutes after its occurrence. (Seismic waves travel at 8 km/sec.) The quake was of strength 7.5 on the Richter scale.

II. Model Calculations

1. Thermal Model for Platform-Passage System

We want to estimate theoretically the thermal deformations with a simplified model, using the fact that the platform (and ceiling of passages) is more exposed to the ambient air than the floor of the passages. If this model describes the observed deformations satisfactorily, it may then be used to estimate the improvement resulting from any suggested future thermal shielding.

Figure 11 shows the northern half of the platform, its dimensions, and the degree of exposure (E) of its various parts to the ambient air. The thick flange, for example, is exposed on both sides, meaning E = 1; the parts below tower and below polar drive house are shielded on both sides, E = 0; and parts exposed on the upper side (deck) but shielded on the lower side (passage ceiling) have E = 1/2. The thin flange along tower and building is exposed on its upper and lower sides and is shielded sideways by the building wall which is much more massive than the flange, wherefore we gave it only E = 1/4.

A similar drawing was made for the southern half of the platform. The floor of the passages is inside the building (E = 0) for $x \lesssim 22.1$ ft, and has E = 1/2 beyond that.

When the ambient air temperature changes by ΔT, any part of the platform, of length L and exposure E, changes its length by $\Delta L = L\, C_{th}\, E\, \Delta T$, where C_{th} is the coefficient of thermal expansion,

$$C_{th} = 0.99 \times 10^{-5}/^\circ C \quad \text{for concrete.} \tag{16}$$

If one end of this part is fixed and the other is free to move, the free end will tilt by the angle

$$\Delta\phi = \frac{\Delta L}{H} = \frac{L}{H}\, C_{th}\, \Delta E\, \Delta T \tag{17}$$

where

$$\Delta E = E(\text{platform}) - E(\text{passage floor}), \tag{18}$$

and

$$H = \text{height of passage} = 11.0 \text{ ft.} \tag{19}$$

The free end will move vertically by

$$\Delta z = \frac{1}{2} L \, \Delta\phi = \frac{1}{2} \frac{L^2}{H} C_{th} \, \Delta E \, \Delta T. \tag{20}$$

If the center of the platform (x = 0) were fixed, we could start at x = 0 with $\theta = z = 0$, and add up the single deformations of each part with different ΔE. The values at the end of part i then are found from the end of the previous part, i-1, as

$$\phi_i = \phi_{i-1} + \frac{C_{th} \Delta T}{H} L_i \, \Delta E_i \tag{21}$$

and

$$z_i = z_{i-1} + L_i \, \phi_{i-1} + \frac{1}{2} \frac{C_{th} \Delta T}{H} L_i^2 \, \Delta E_i \tag{22}$$

Actually, the center of the platform is not fixed. Instead, we will assume that the platform-passage system is supported (not fixed) by the building walls at two places, right below A and B in Figure 1, separated by 42.4 ft. After having found z_A and z_B from (22), we must apply a constant correction of $K = (z_B - z_A)/42.4$ ft to all values of (21), and a linear correction of $(z_A + z_B)/2 + Kx$ to all values of (22).

2. Result for Present State

By this method Figure 12 was calculated. At level A, for example, we find a tilt of $\phi_A = -0.833$ arcsec/°C, which is in error by 10% as compared to the actually observed value of -0.92 arcsec/°C from equation (6). A summary of all three levels is given in Table 4 of the following section. Regarding the crudeness of our model, the agreement between model and observation is good enough.

The model so far discussed would not be able to explain the full tilt of the main bearing on top of the tower. If we consider only that the tower rests asymmetrically on the platform, supported at points W_1 and W_2 which are separated by 22.5 ft (Figure 1), we obtain from our model calculation a tower tilt of $[z(W_1) - z(W_2)]/22.5 = -0.163$ arcsec/°C, which is too small by a factor of 4.1 as compared to the measured value of equation (9).

The tower will have a deformation of its own. Measured between wall centers, the average tower length (NS) is L = 19.7 ft, its height is H = 15.7 ft, and the location of level B^* is b = 3.2 ft north of the tower center. Floor and ceiling are not exposed, while the vertical walls have E = 1/2. When the air temperature rises by ΔT, then L increases by $\Delta L = L\ C_{th}\ E\ \Delta T$, and the north wall moves north by 1/2 this amount, $\Delta x = (1/4)\ L\ C_{th}\ \Delta T$. The upper north corner of the tower would tilt south by the angle $\Delta\alpha' = 2\ \Delta x/(H/2) = (L/H)\ C_{th}\Delta T$, if the bending stiffness of the tower ceiling were negligible as compared to that of the walls. Actually, we will assume that both are equal, which gives 1/2 this angle, or $\Delta\alpha = (1/2)\ (L/H)\ C_{th}\Delta T$. The opposite occurs at the upper south corner, and these two end-moments let the tower ceiling deform downward in a parabolic shape ($\Delta z \propto x^2$), with its tilt angle ($\Delta\phi = dz/dx$) linear in x. At the location of B^* we then expect from this model a south tilt of $\Delta\phi = \Delta\alpha\ b/(L/2) = (b/H)\ C_{th}\ \Delta T =$ 0.416 arcsec/°C. In total, counting north as positive, we have

$$
\begin{aligned}
\text{Main bearing, } B^*:\quad & \text{support points} &&= -0.163 \text{ arcsec/°C} \\
& \text{wall deformation} &&= \underline{-0.416 \text{ arcsec/°C}} \\
& \text{total, } \Delta\phi(B^*) &&= -0.579 \text{ arcsec/°C}
\end{aligned}
\qquad (23)
$$

This agrees within 11% with the measured value of -0.65 from equation (9), which is considered satisfactory.

3. The Resulting Polar Shaft Tilt

If the upper shaft end at the main bearing is moved up by Δz, and is moved north by Δx, the resulting shaft tilt follows from the geometry of Figure 1 as

$$\Delta\phi = (2.70\ \Delta x - 3.46\ \Delta z)\ 10^3\ \text{arcsec/ft}, \tag{24}$$

and the opposite signs hold for a movement of the lower end at the tail bearing.

The thermal movements at both ends can be obtained from our thermal model. Omitting the rather tedious details of the calculations, we find for the present (unshielded) state, in arcsec/°C and plus meaning north for warmer air.

-0.27 from Δz main bearing

-0.12 from Δx main bearing

-0.27 from Δz tail bearing

+0.37 from Δx tail bearing

$$\Delta\phi = (-0.29 \pm 0.11)\ \text{arcsec/°C} \tag{25}$$

The estimated error is derived from the assumption that each of the four single items may be wrong by ± 20% rms. Although the shaft tilt of (25) is only 1/3 of the tilts at the level locations, it still contributes a pointing error which cannot be neglected, up to 20-30 arcsec between summer and winter.

III. Suggested Improvements

1. Heat Pads for the Deck

If our thermal model makes sense, then the upper part of Figure 12 shows that the thermal deformations of the deck-passage system should be improved by shielding most of the upper deck against ambient air, with the aim of making the exposure E of the upper deck more similar to that of the passage floors, since ΔE is what matters for equations (21) and (22). First, it turned out that a simple thermal insulation of the upper deck is not sufficient, because the thick flanges would still follow the ambient air completely, only with a longer time delay. The next suggestion was to build a house, from the tail bearing over the polar shaft and tower, up to and including the polar drive house. The roof and walls should be thermally insulated, and the inside air should be kept at constant room temperature and well ventilated. A rough design was made by John Ralston, but it was turned down for being too expensive ($55,000) and rather laborious.

The present suggestion is to use electric heat pads. The outer rim of the platform (walk way) is raised by six inches, and the pads should be embedded in all deeper parts of the south platform; on the north platform, they should fill out all the deeper parts between the tower wall and the beginning of the brake castings. By "heat pads" we mean that electric heat coils are laid out in a regular pattern on the lower parts of the deck, with some thermostats at the concrete floor. A non-combustible thermal insulation then is sprayed on, about three inches thick, and this is topped off by a three inch layer of concrete wearing course. The covered floor of the deck should then be kept at a constant temperature (25°C, say). The details and cost estimate will be worked out by J. Ralston.

2. Model Calculations

For estimating the improvement to be expected, we use again our thermal model, but now with the lower parts of the deck at constant temperature. Omitting the details, the results are shown in Figure 13, where it was left open up to which northern point the pads should be extended (see case a, b, c in Figure 13); since not much difference is expected, it was decided that case a is all we need. The area to be covered by the pads then is

$$\text{padded area} \;=\; 815\ \text{ft}^2. \tag{26}$$

A comparison of the padded deck with the present state is given in Table 4. We see that we obtain a rather good improvement for all items listed. The actual amount of the improvement will depend on the correctness of our thermal model; but at least for the present state, the model agrees fairly well with the actual measurements.

TABLE 4

Comparison of Observed Tilts with Model Calculations, and Improvements to be Expected from Padding the Deck and Insulating the Tower Walls

Location	Tilt, $\Delta\phi$ (arcsec/°C)				Improvement from Pads and Shielding
	Present State			Deck Pads and Tower Shielding	
	Measured	Model	Error		
A South passage	-0.92	-0.833	-9%	-0.294	65%
B North passage	+1.28	+0.926	-28%	+0.294	68%
C Tail bearing	-1.06	-1.201	+13%	+0.043	96%
B* Main bearing	-0.65	-0.579	-11%	-0.184	68%
Location	Movement, Δz (10^{-2} mm/°C)				
C Tail bearing		-2.414		-0.333	86%
X=0 Center		+0.834		+0.286	66%
	rms error = 17%			rms improvement = 76%	

3. Insulating the Walls of the Main Bearing Tower

As to the resulting tilt of the polar shaft, it turns out that padding the deck is not enough, we must also give the vertical tower wall some thermal insulation, because the first item of equation (25), the movement Δz of the main bearing, is not changed by padding the deck, and the total tilt $\Delta\phi$ would still be too large. Leaving the exposure E of the tower walls as a free parameter (at present, E = 1/2), and omitting all details of the calculations, we find for the padded deck a shaft tilt of

$$\Delta\phi = (+0.173 - 0.663\ E)\ \text{arcsec}/°\text{C} \qquad (27)$$

It is very fortunate that we have opposite signs in this equation. If we choose

$$E = 0.261 \qquad (28)$$

then the resulting shaft tilt is zero (or would be, if our thermal model were exactly correct).

We suggest to spray onto the vertical tower walls, all around and full height, a layer of thermally insulating material, for example, isofoam. We call t_i the thickness of this layer, and t_c = 3 ft the concrete wall thickness. Calling k the thermal conductivity, we have

$$\left.\begin{array}{lll} \text{concrete} & k_c = & 12.0 \\ \text{isofoam} & k_i = & 0.15 \end{array}\right\} \frac{\text{BTU}}{\text{h ft}^2\ °\text{F/inch}} \qquad (29)$$

With the tower inside at constant room temperature, the exposure of the wall is

$$E = \frac{1}{2}\,\frac{t_c/k_c}{t_c/k_c + t_i/k_i} \qquad (30)$$

and for obtaining E = 0.261, we need a layer thickness of

$$t_i = 0.916\ t_c\ k_i/k_c = 0.41\ \text{inch.} \tag{31}$$

Regarding the uncertainty of our model, we may round this off and specify a layer of 1/2 inch thicknesss.

4. Cost Versus Reliability

So far, we have discussed the cheapest alternative: heating the deck for making it deform similar to the passage floor, and shielding the tower just enough to let the two terms of equation (27) cancel each other. But we may feel somewhat uncertain about the validity of our thermal model used.

The most reliable alternative is avoiding thermal deformations altogether, by spraying the outside of the whole building with a thick layer of isofoam, from the ground level over passages and deck up to the top of the tower. The heat coils could then be omitted.

Unshielded, the outside of the walls follow the ambient air changes almost completely; see Figure 6. If we want to cut down these changes by a factor q, we need a thermal conductivity of the shielding 1/(q+1) of that of the wall, and the layer thickness needed is

$$t_i = (q+1)\ t_c\ k_i/k_c = (q+1)\ 0.45\ \text{inch.} \tag{32}$$

The measured local tilts at the bearings are given in (8) and (9) with an average of 0.86 arcsec/°C, while the estimated resulting shaft tilt is 0.29 arcsec/°C from (25). Regarding our uncertainty, we use the average of both, 0.575 arcsec/°C. With $\Delta T = 60°C$ between summer and winter, this amounts to a present ptp shaft tilt of 34.5 arcsec. If we want to reduce this to 6 arcsec, say, we need $q = 34.5/6 = 5.75$; and with (32) we need a thickness of the isofoam layer of

$$t_i = 3.0\ \text{inch.} \tag{33}$$

The surface to be covered is about 18,000 ft^2. At present we have no good cost estimate. The only tentative quotation is $\$3/ft^2$ for spraying the yoke arms. Since most of that is labor, the building walls should be less, say, $\$2/ft^2$, and shielding the whole building would amount to about \$36,000, whereas a rough estimate of the first alternative (deck pads and tower) gave \$11,000.

A decision as to these alternatives can only be taken after obtaining better cost estimates, including the possibility of just buying material and equipment and doing the work inhouse.

5. Regulation of Inside Temperatures

Pump motors and electronic equipment provide so much heat that the 140-ft building needs only cooling. Although heating is provided for the coldest winter days, it is actually almost never used (except in the lobby behind the entrance door). Temperatures are regulated with thermostats at various places, but some rooms are better regulated than others.

Inside wall temperatures were measured at six places; see Table 2. They stayed mostly fairly constant. The largest variation is found in the pump room at the south side of the second floor (ΔT_4 = 5.7°C ptp during 49 days), which has no thermostat. The next largest variation is found at the north wall, east corner, on the first floor (ΔT_3 = 5.1°C ptp), which is at a distance of 38 feet from the only thermostat on this floor, and separated from it by the central elevator shaft and staircase walls.

The largest angular deformation not yet explained is the average building tilt, see (A+B)/2 in Figures 6 and 7, with 15 arcsec ptp; see Table 1. Unfortunately, T_3 and T_4 were measured only from February 6 on, whereas the largest variation of (A+B)/2 occurred earlier during January 16-18.

Since B depends stronger on the ambient air than A, with B = -1.40 A from equation (5), the influence of the ambient air is omitted if we consider the quantity A+B/1.40, which then should depend only on the inside wall temperatures of the building. Considering only the unregulated places T_3 and T_4, we derive (from the geometry of the building, the thermal expansion of concrete, and a wall exposure of E = 1/2) the theoretically expected correlation as

$$A + B/1.40 \;=\; 1.07\ (T_4 - T_3)\ \text{arcsec/°C}. \qquad (34)$$

This correlation is checked in Figure 14. Although there is a large scatter, we see a fairly good correlation with about the right slope, deviating from it by ± 2.6 arcsec rms.

This means that the inside temperatures of the 140-ft building should be regulated by thermostats at some additional places, if a really high pointing accuracy is wanted (and is not prevented by other causes).

5. Other Items

In addition to the deformations of the building, we have the large deformations of the two yoke arms and the polar shaft (von Hoerner 1975b), to be improved by spraying on a 1.5 inch thick layer of isofoam. Two thermistors each should be mounted in the steel surface under this insulation, just in case, in order to measure any remaining thermal gradients across these members, and to correct for it in the computer if necessary.

A complete treatment of the refraction, using weather data from the interferometer, was worked out and will be given soon.

The only item not yet investigated is the thermal deformation of the upper structure, of cantilevering dish rim and of feed support legs. This is in preparation.

Finally, I would like to thank Fred Crews for setting up all the equipment and readings and for his constant help, and John Ralston for providing Figures 1, 2, and 3 of the building.

References

von Hoerner, S., and Wong, W.Y., 1975: "Gravitational Deformations and Astigmatism of Tiltable Radio Telescopes", IEEE Trans. Antennas and Propagation AP-23, 689.

von Hoerner, S., 1975, a: "Focal Length Adjustment of the 140-ft", NRAO Electronics Division Internal Report No. 160.

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____________ 1976, "The Design of Correcting Secondary Reflectors", IEEE Trans. Antennas and Propagation (in print, May 1976).

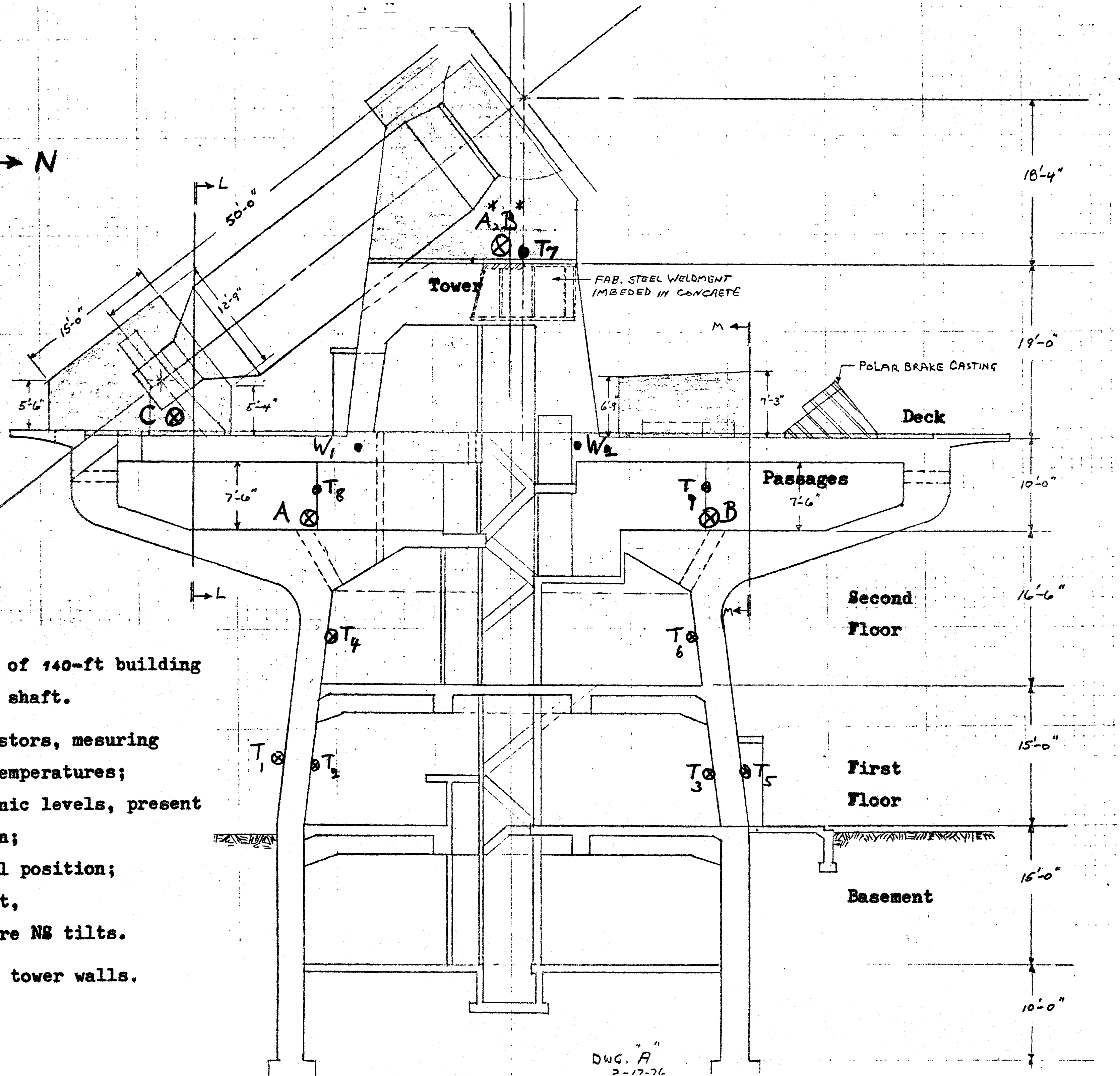

Fig. 1. Side view of 140-ft building and polar shaft.

T_1 ... T_9 = thermistors, mesuring wall temperatures;

A, B, C = electronic levels, present position;

A^*, B^* = original position;

A^* measures EW tilt,

A, B, B^*, C measure NS tilts.

W_1, W_2 = center of tower walls.

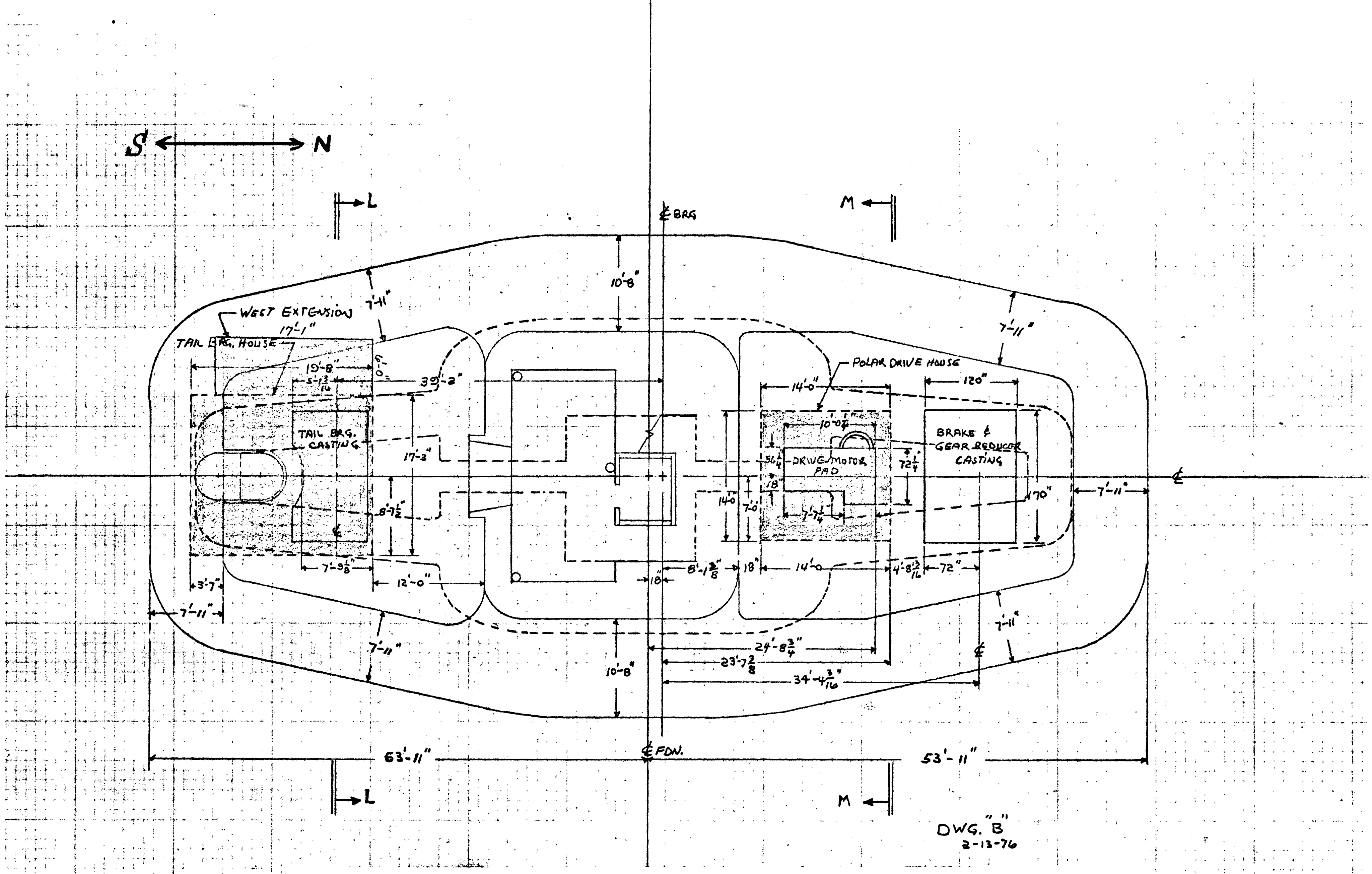

Fig. 2. Deck plan.

Broken lines = ceiling of passages.

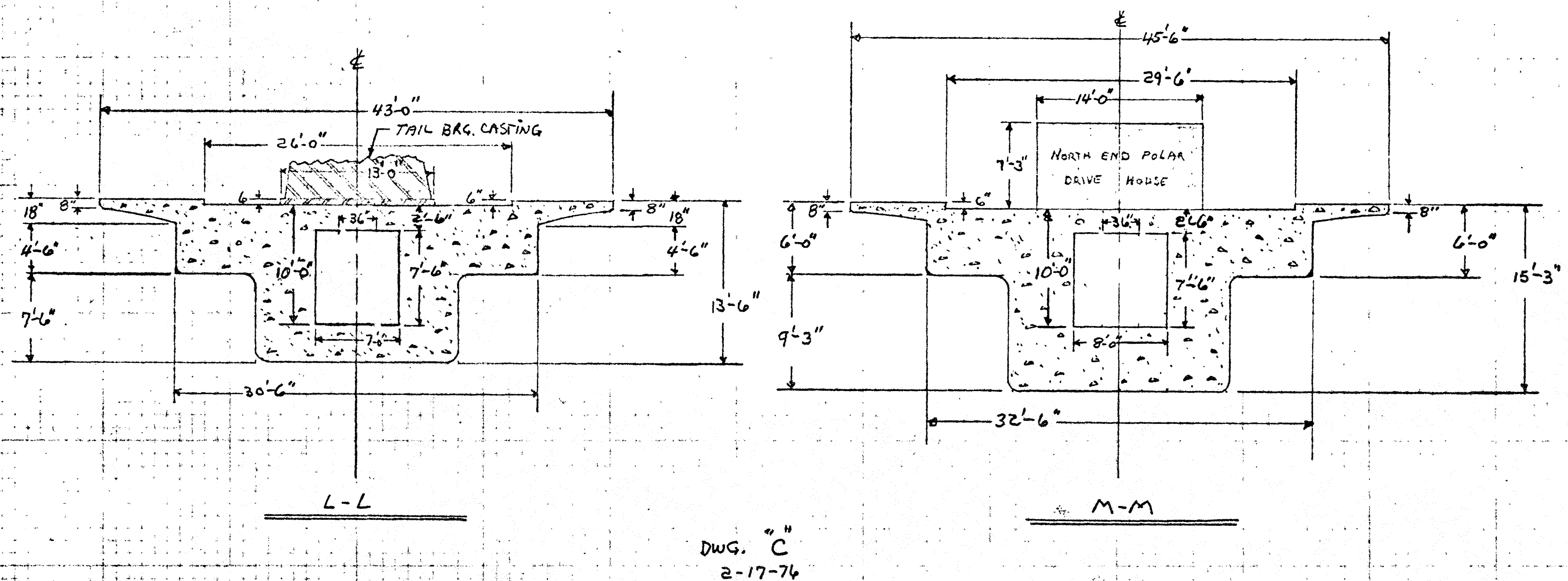

Fig. 3. Passages.

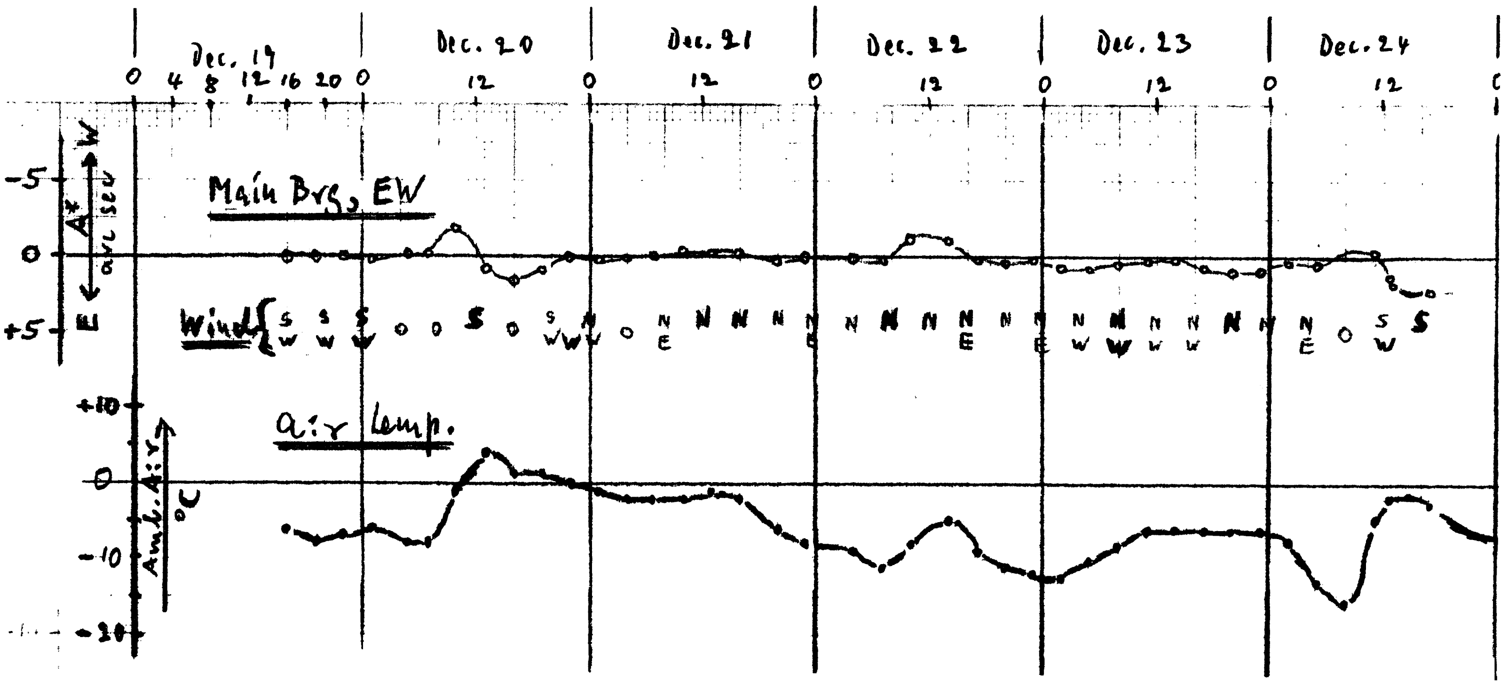

Fig. 4. East-West wiggle at main bearing, caused by strong sunshine, see high rise of ambient air temperature around noon.

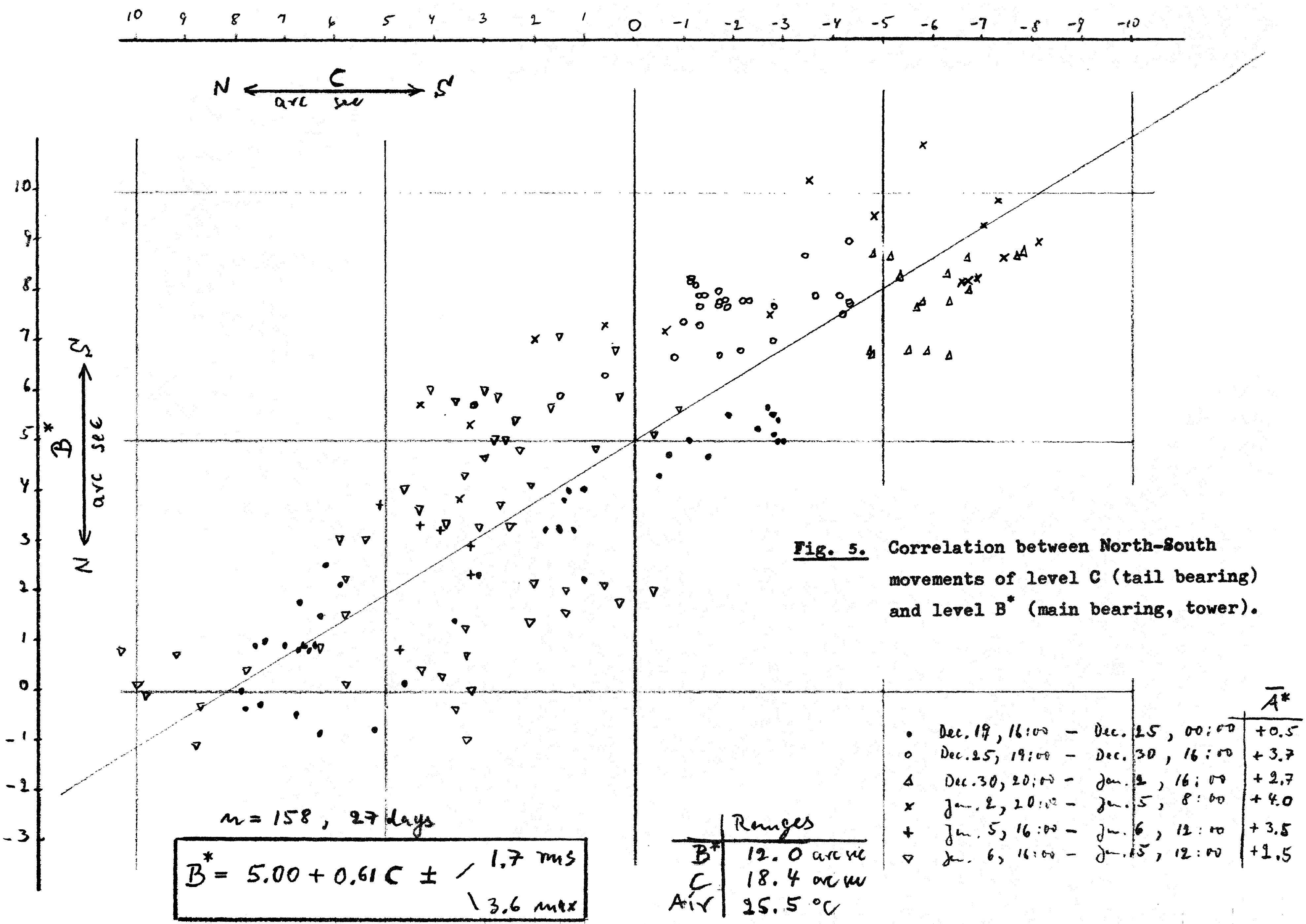

Fig. 5. Correlation between North-South movements of level C (tail bearing) and level B* (main bearing, tower).

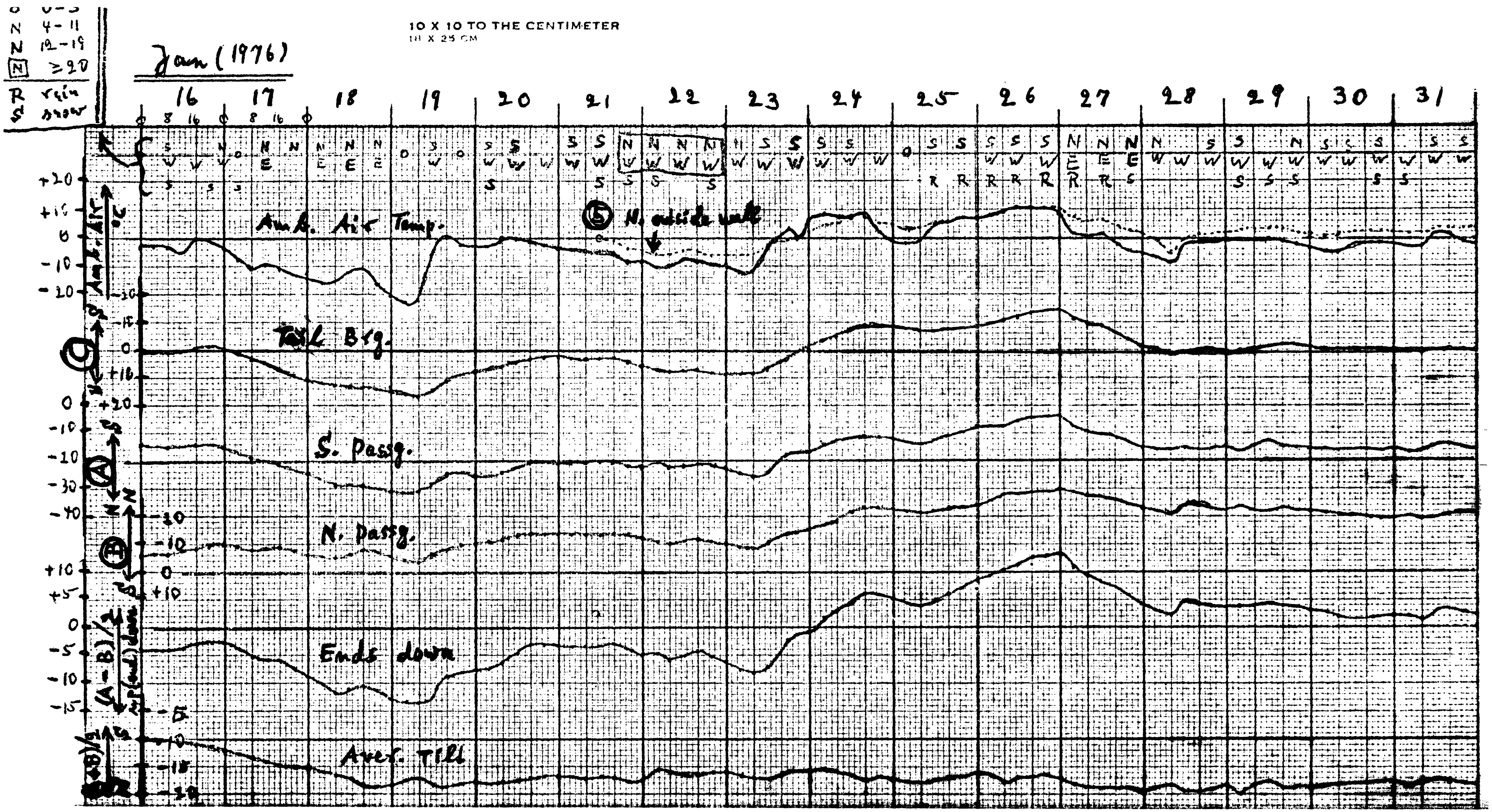

Fig. 6. Thermal deformations of concrete building (16 days): six readings per day.

At top, wind and percipitation. Next, ambient air temperature; beginning Jan. 21, also the temperature at one inch depth in the outside of the north wall.

Angular deformations are measured every four hours with three electronic levels, C, A, B; mounted at tail bearing, south passage and north passage ways. In seconds of arc.

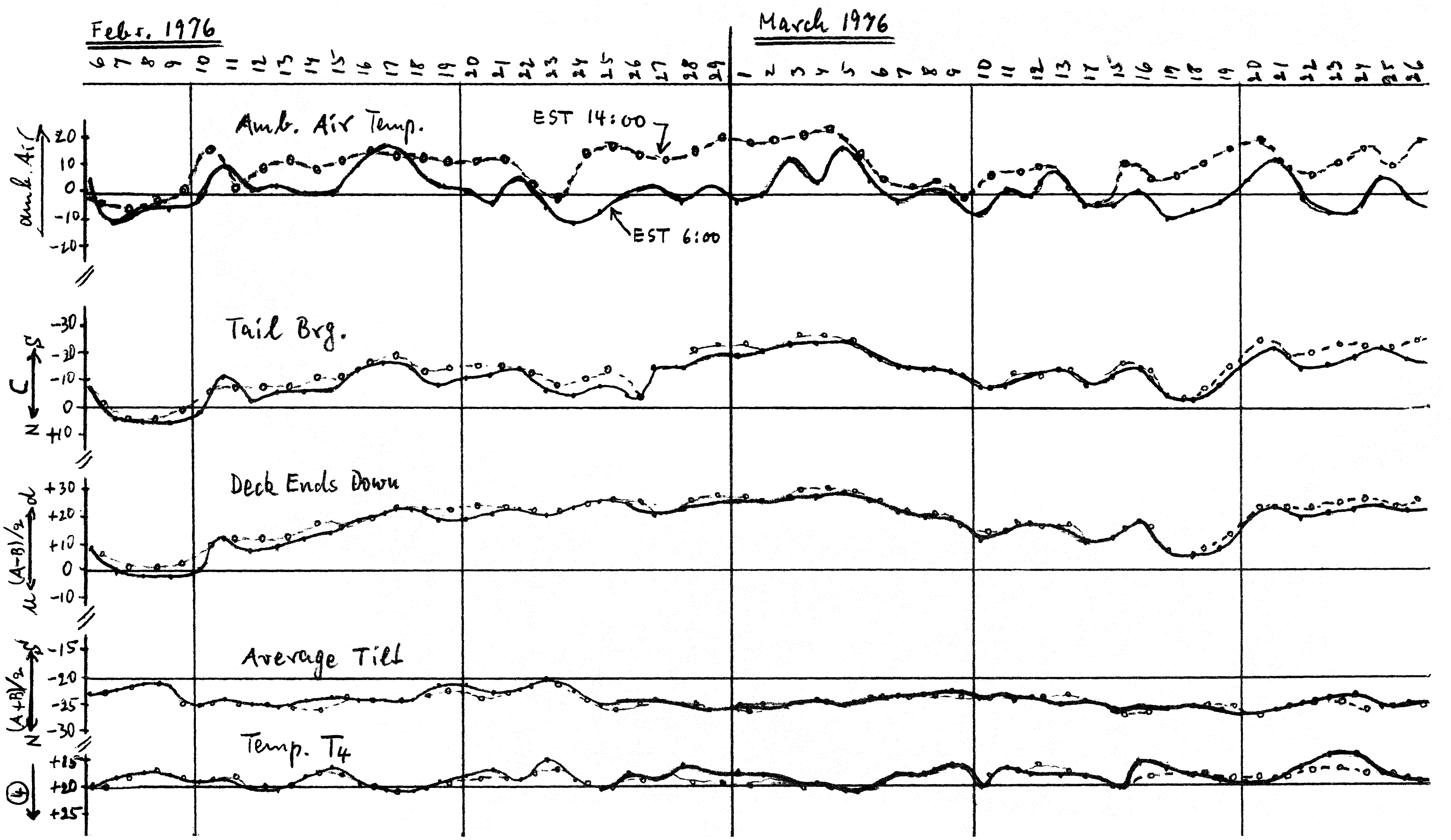

Fig. 7. Thermal deformations of concrete building (50 days); two readings per day, at EST 6:00 and 14:00.

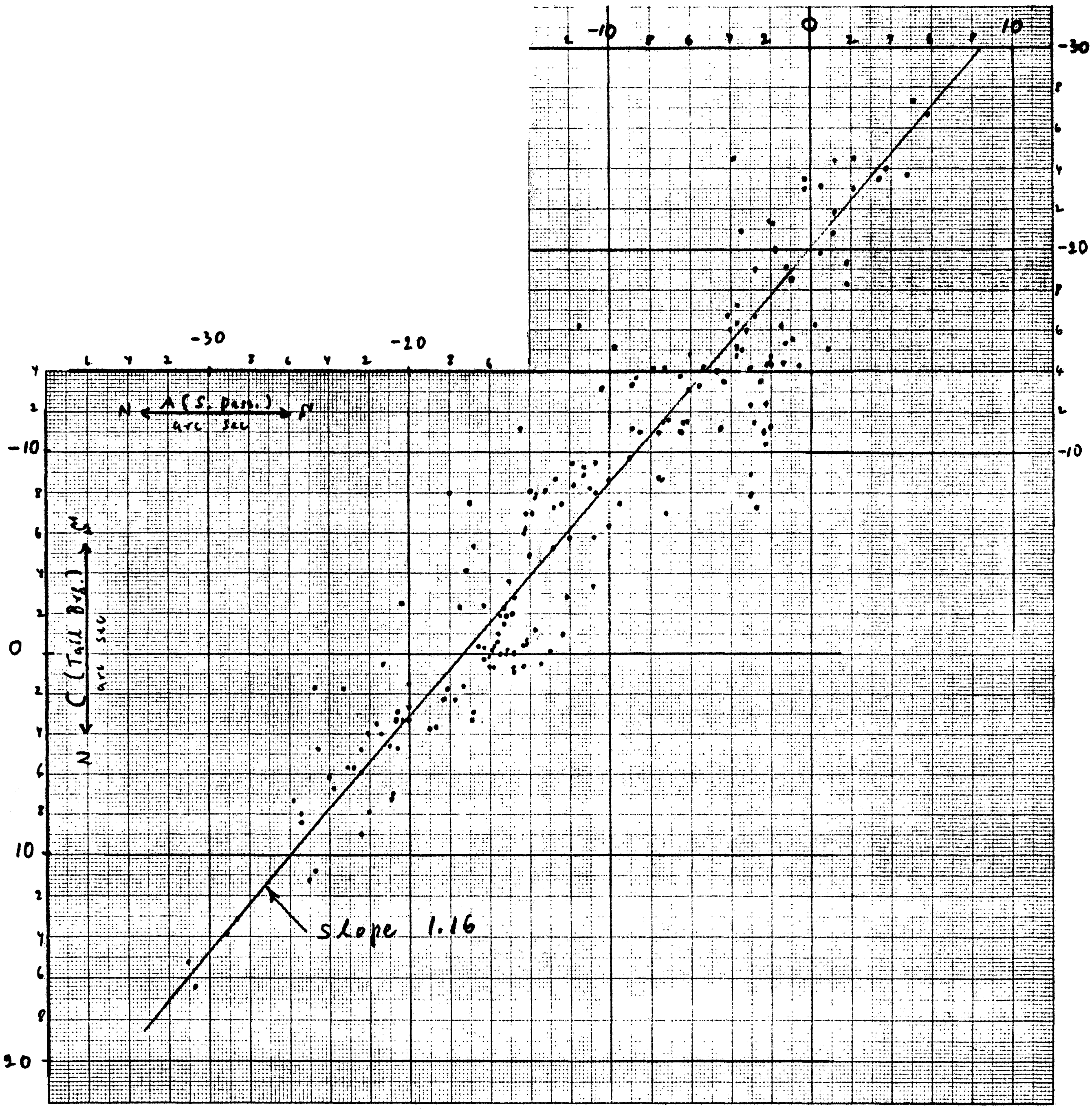

Fig. 8. Correlation between the NS tilts of level A (south passage) and level C (tail bearing).

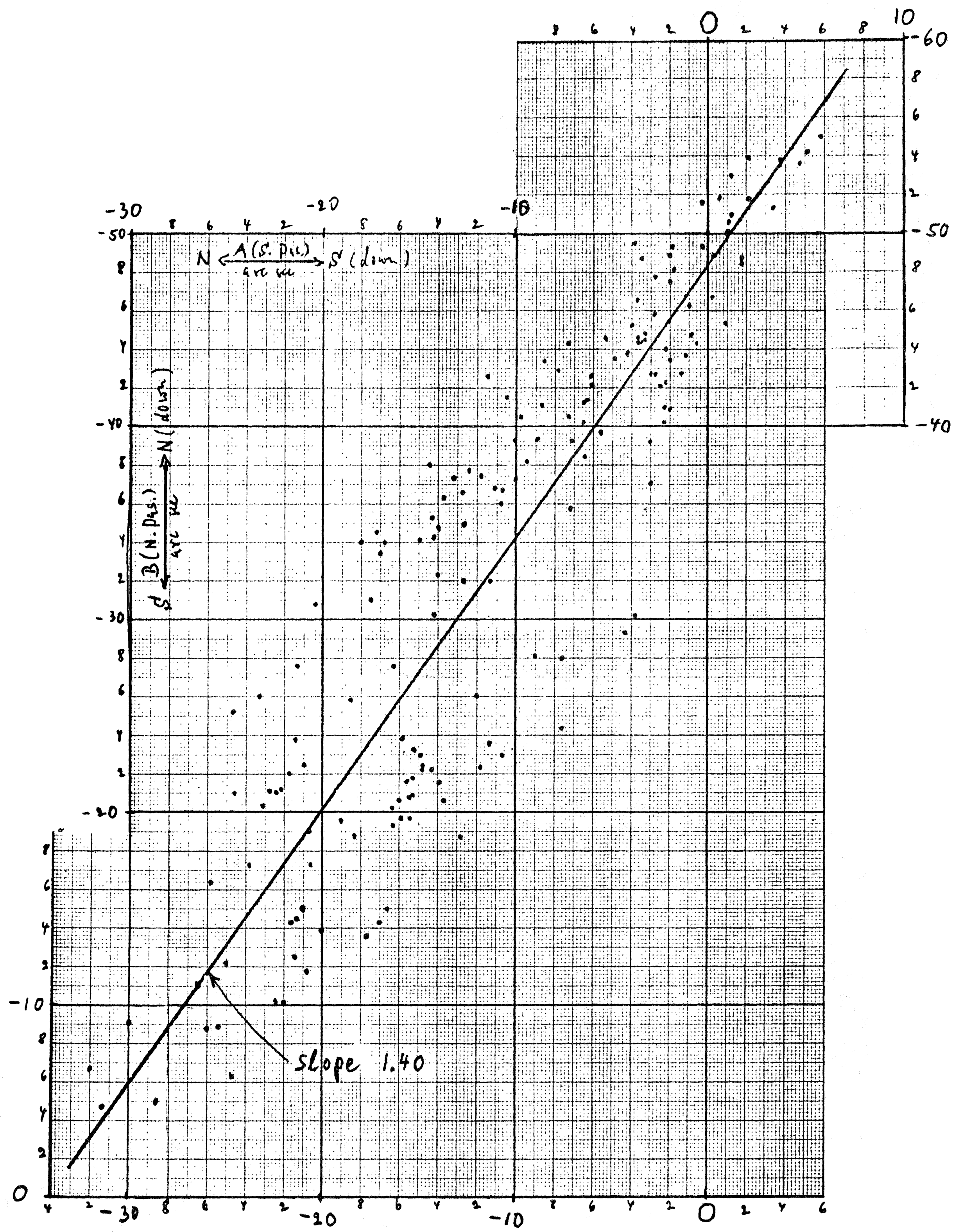

Fig. 9. Correlation between the NS tilts of level A (south passage) and level B (north passage).

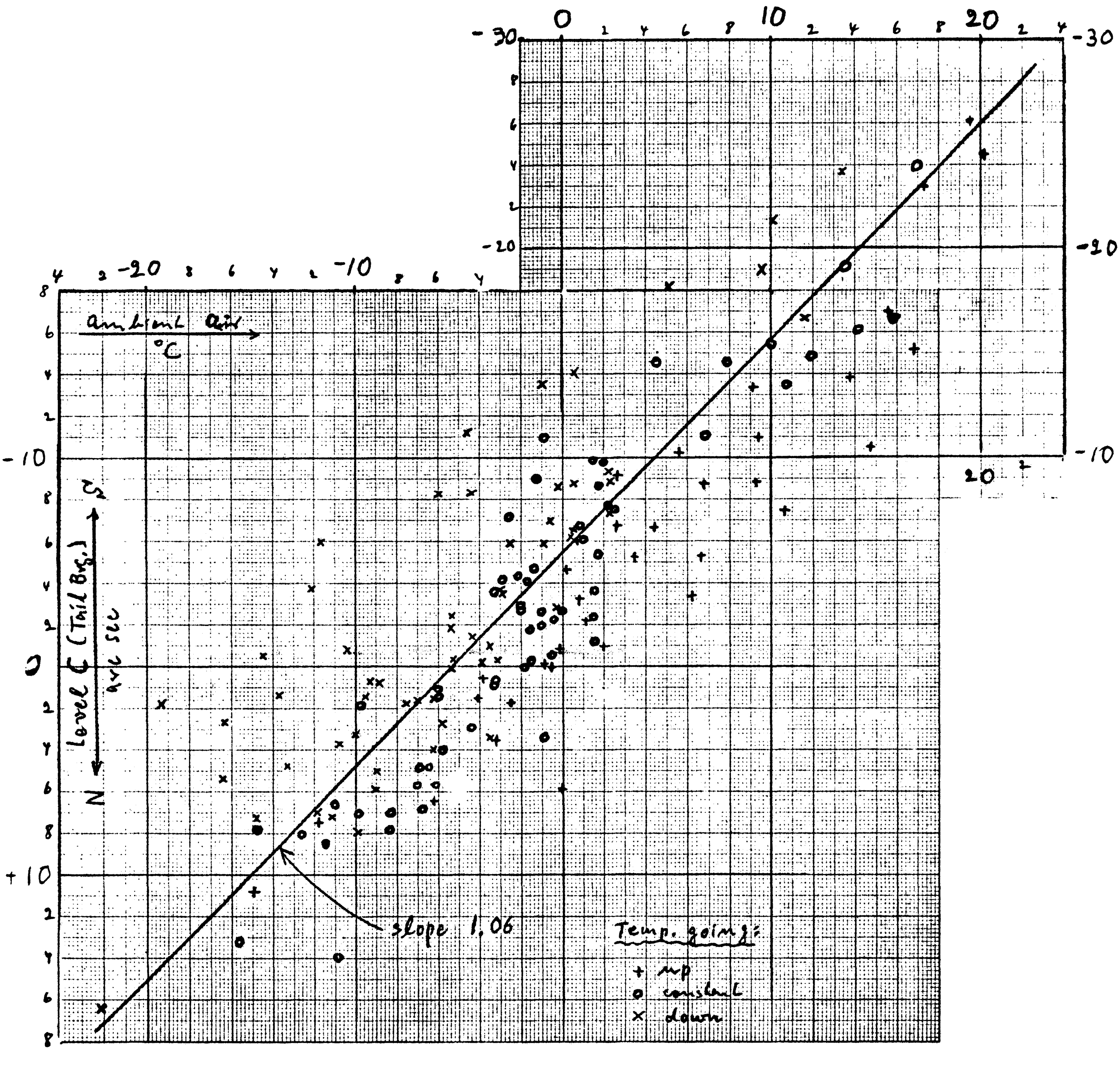

Fig. 10. Correlation between NS tilt of level C (tail bearing) and ambient air temperature. The scatter is mainly due to a time delay of the tilt. The best-fitting line should go through the open circles, and should have all x signs above and all + signs below it.

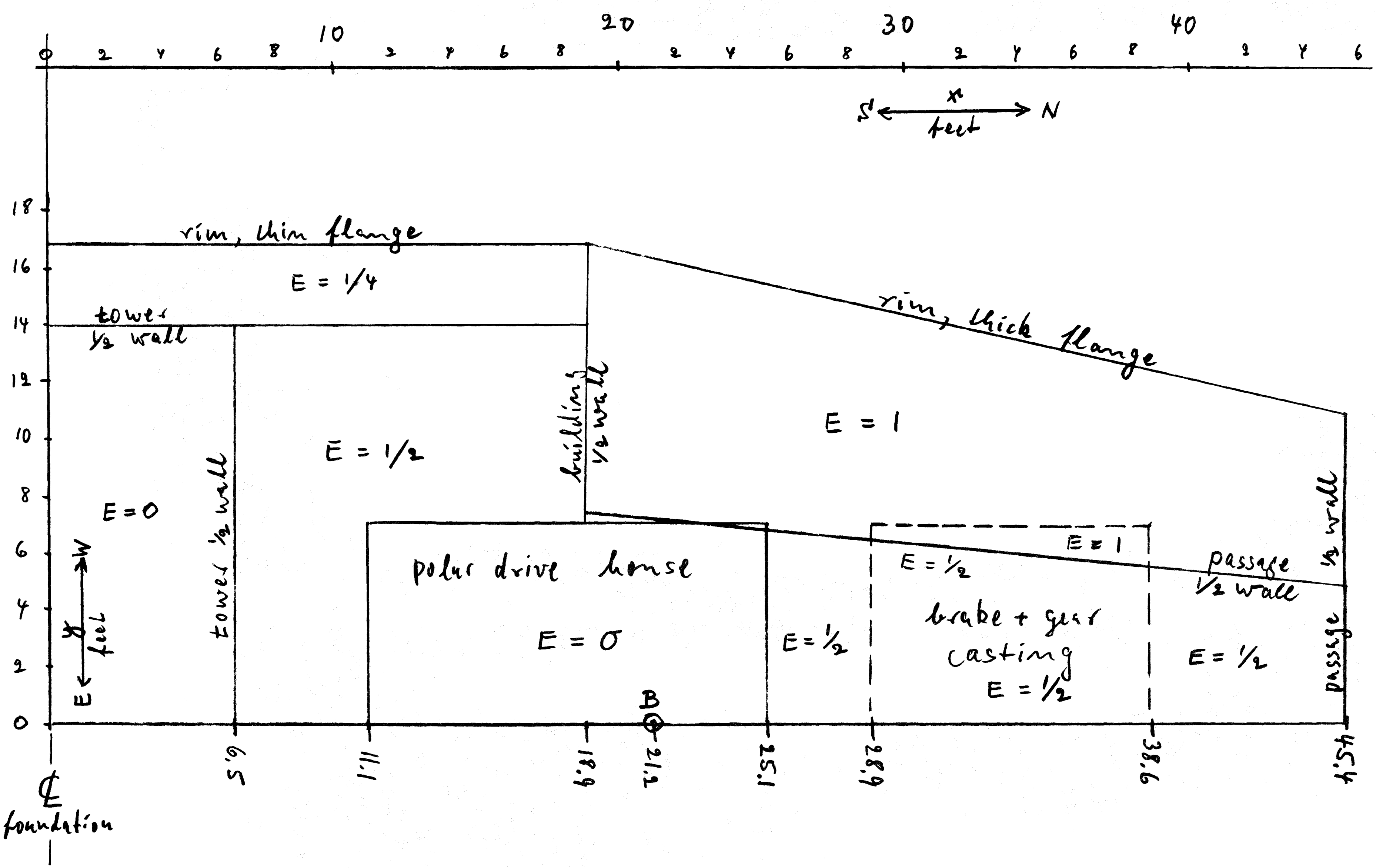

Fig. 11. North-West quarter of 140-ft deck; present state (no shielding).
E = degree of exposure to ambient air.

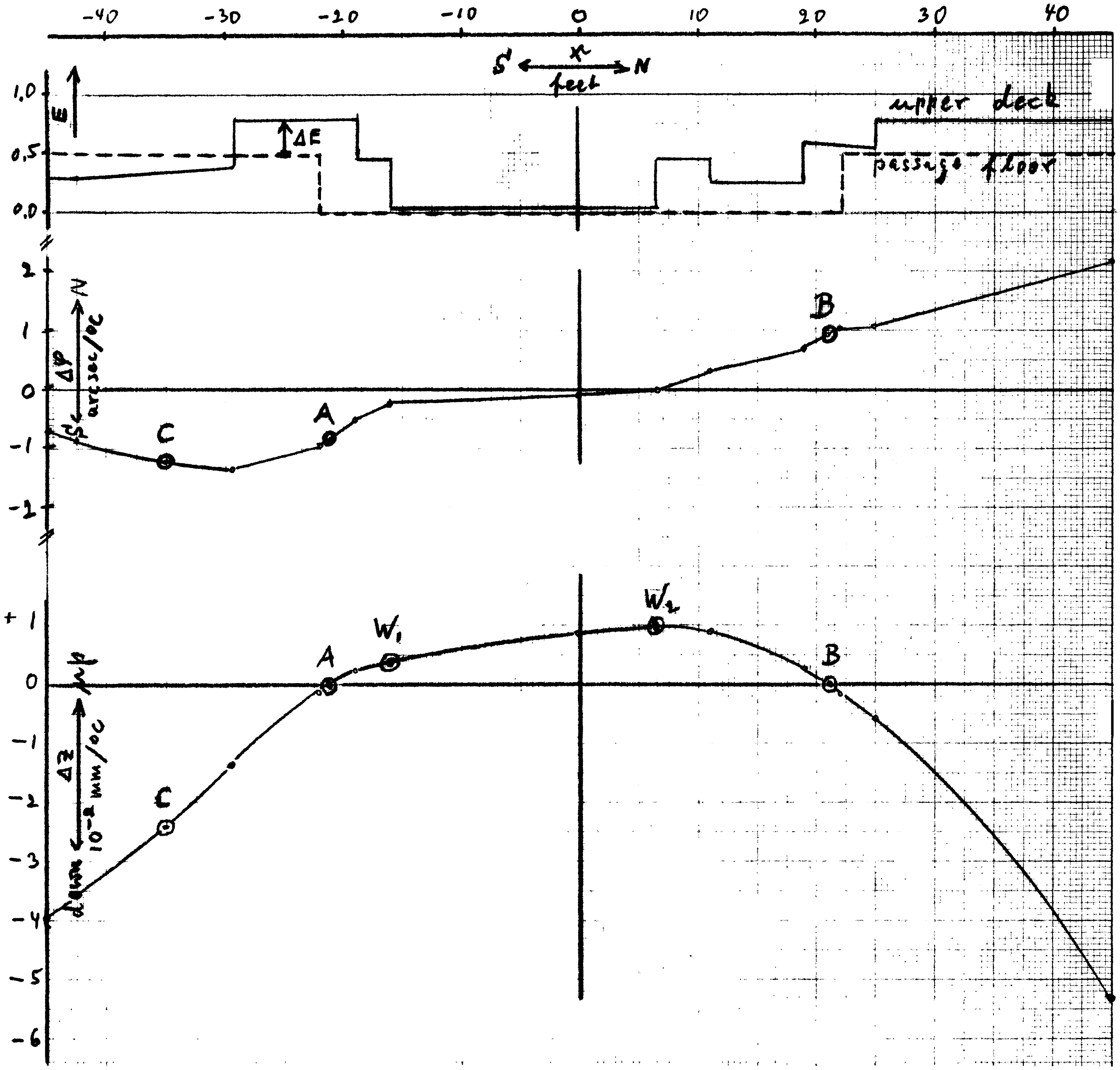

Fig. 12. Calculated thermal deformations along 140-ft deck, for present state (no shielding).

E = degree of exposure to ambient air,

Δφ = angular tilt, in arcsec/°C,

Δz = vertical movement, in 10^{-2} mm/°C.

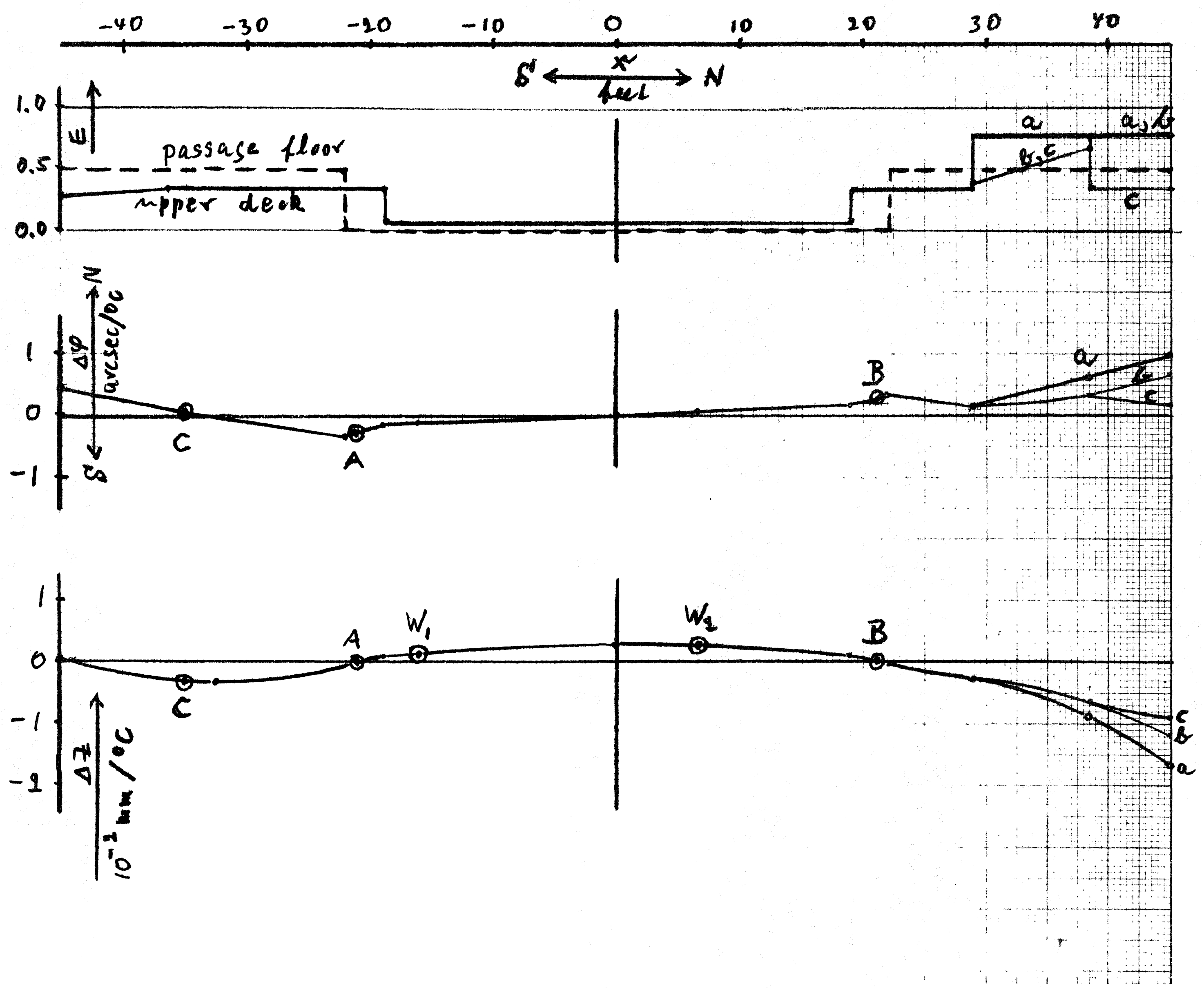

__Fig. 13.__ Calculated thermal deformations along 140-ft deck, with heat pads at constant temperature, covering all lower parts of deck, from end of south deck to a) start of brake casting on north deck,

b) end of brake casting,

c) end of north deck.

E = degree of exposure to ambient air,

Δφ = angular tilt, in arcsec/°C,

Δz = vertical movement, in 10^{-2} mm/°C.

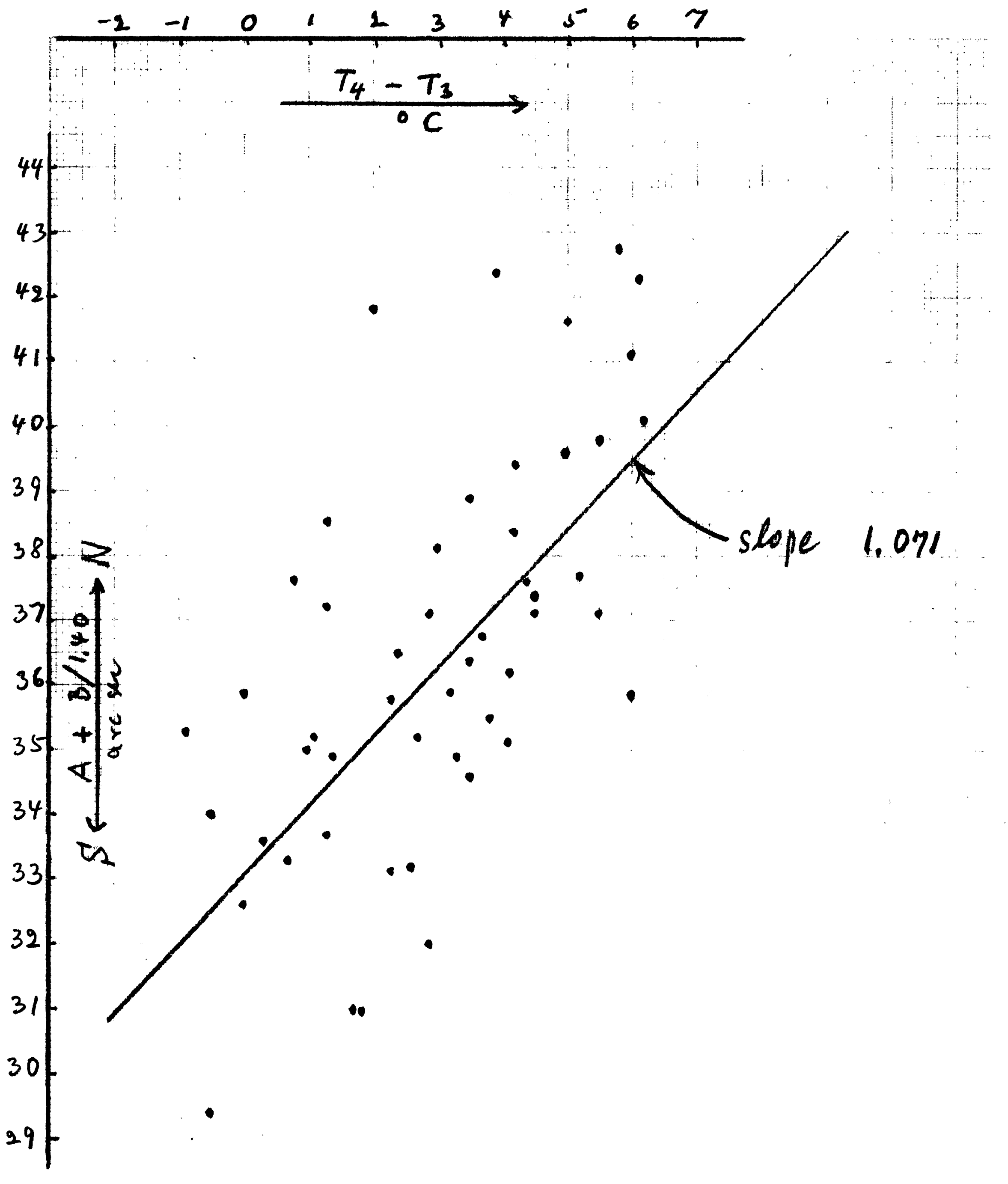

Fig. 14. Correlation between average tilt of building (after omitting ambient air influence) and two inside wall temperatures (where temperature is not thermostat-regulated). One reading per day, at EST 6:00, on 49 days. For locations, see Fig. 1.

The slope of 1.071 is the theoretically expected one.