W-Y. Wong
Memo No. 92
May 12, 1977

Thermal Deformations of the 25-M Telescope Backup Structure Protected by an Astrodome

Summary:

There are two causes of thermal deformations on the telescope: deformation due to vertical temperature gradient (ΔT) and different thermal lags between heavy and light members during steep rise and fall of the ambient air temperature ($\dot{T}$). Computer analysis on both effects were carried out for the backup structure. Field data on $\dot{T}$ are readily available, but we do not have data on ΔT inside existing domes with strong air circulation. With duct works and registers of air circulation system mounted on the walls of the astrodome, a ΔT of not more than 3^{o}c during days with closed door is considered realistic; during nights with open dome and without air circulation, $\Delta T = 2^{o}$c is considered realistic.

Using this data in the analysis and including all the other error contributions, we find that the telescope can operate at $\lambda = 1.2$mm for 83% of the time, and at $\lambda = 2.0$mm for 100% of the time, during clear sky observation periods.

Regarding the planned improvements of the design (memo no. 79), we assume a reduction of the manufacturing accuracy of the surface plates to 25 μm and of the telescope measuring technique to 15 μm. The telescope then can operate at $\lambda = 0.8$mm for 75% of the time and at $\lambda = 1.2$mm for 100% of the time.

Thermal analysis of the backup structure:

The deformation due to temperature difference on various parts of the telescope will degrade the surface accuracy. Solar radiation usually is the main cause of the large temperature difference on various parts of the structure when one part of the telescope is exposed to the direction of the sun while the other part is under the shade (ΔT in closed dome). Additionally, the telescope structure is composed of many structural members of different shapes, each one has its own thermal time constance. A change of ambient air temperature will cause different thermal lags on various parts of the telescope.

For every member m on the structure, the temperature effect due to temperature gradient is defined as:

$$t_m = C_{th} \times z_m \times \frac{\Delta t}{z} \qquad (1)$$

where $C_{th} = 1.17 \times 10^{-5}/c^{o}$ for steel
z_m = average elevation of member m
$\Delta t/_z$ = temperature gradient on the telescope

and the temperature effect due to thermal lag is defined as:

$$tm = \tau \times \omega \times \dot{T} \qquad (2)$$

where τ = thermal time constant for the structure member 68.9×10^{-3} hr/mm (1.73 hr/in.) for tubular member painted white, 50% reduction for open channel or I-beam.
ω = wall thickness of the member
$\dot{T}$ = time derivative of ambient air temperature

These effects cause a shift of the beam and a change of focal length. These movements of the best fit paraboloid will not produce error signals to the angular encoders at the elevation and azimuth bearings to cause adjustments. Other means are needed to make these corrections:

(1) manual adjustments by observers to resolve for an optimum focal length at hourly intervals;

(2) focal adjustments as a function of the hour of the day, incorporated in the pointing program and driven by the on-line computer (it is possible after a large amount of temperature data is collected and the correlations are resolved);

(3) by using temperature sensing device to make direct measurements and corrections; this is considered a feasible, yet to be proved a workable scheme.

Vertical temperature difference and focal adjustment are correlated, as already verified by the 36-foot telescope of Tucson (E. Conklin's memo dated September 28, 1970).

The analytical results of the surface error contribution due to temperature effects are listed in Table 1. The values used in the telescope performance analysis are shown in the last column of the table. For thermal lag, the analytical value is considered as realistic as those from gravity effects since the wall thickness of each member in the structure is well defined. For the values from temperature gradient effect, care must be exercised in using them in predicting the surface error of the telescope. Because the gradients used in the analysis are idealized distributions, the result shows a factor of 16 improvement in the vertical gradient case if the focal length is adjustable. A factor of 4 was achieved in the 36-foot telescope of Tucson when adjustment of focal length was carried out based on the measurement of temperature of various locations on the structure. There is no attempt to correct the pointing error for its small magnitude. The equivalent surface error due to the deviation of beam is combined into the surface error budget of 5 μm/°C.

TABLE 1 - Analytical results of thermal effects for the 25-M telescope backup structure

Thermal load	pointing error (arc-sec)	rms surface error (μm) from analysis no focal adjustment	 with focal adjustment	rms surface error (μm) adopted for error budget
thermal lag, $\dot{T}=1^{o}C/hr$	0	40	8	8
z gradient, $\Delta = 1^{o}c$	0	16	1	5
y gradient, $\Delta T=1^{o}c$	.8	0	0	

Special features of the astrodome:

The enclosure of the telescope is justified and was described in detail in Chapter IV of the 25-M proposal. The astrodome concept was adapted for the reason that the door can be open during a calm, clear night and the radome material loss is eliminated during the observation. In order to support the door, plus the structural integrity required, the astrodome has built-up framework surrounding the three sides of the telescope, covered by sidings of ordinary building material. The framework provides space for a network of conduits for the air circulation system. This provision will enable a forced circulation of air within the dome when the door is closed during the daytime when the sky is clear. Quick exchange of air between the upper and lower level will reduce the temperature gradient effect. Additionally, the large space between the rim of the telescope and the dome affords the free movement of air between the front and the back of the dish. Maintaining a 3°c average temperature difference within the dish structure is considered economically feasible. Its necessity is not entirely certain, but the provision can be implemented without budgeting a large amount of money to provide optional ventilation in addition to the circulation. This exchange of inside/outside air enables the telescope temperature to follow the outside ambient air temperature; hence no sudden rise or fall in temperature that the telescope will have to experience when the astrodome opens or closes its door.

Special features of the telescope:

Equation (2) shows that if the wall thickness of all members in the structure are identical, the time-derivative of temperature effect ceases to exist. It is not possible to do so since there are other design parameters to be taken into account in sizing the members. But it is possible to keep the variation of wall thickness for all members within a limit so that the overall time constant of the structure ($\Delta\tau$) is limited to, say, 20 minutes. Then the variation of wall thickness can be defined as follows:

$$\Delta\tau \leq \tau \times \Delta\omega \qquad (3)$$

where $\Delta\tau = 20$ min. = 1/3 hr.

$\tau = 68.9 \times 10^3$ hr/mm (1.73 hr/in.)

$\Delta\omega$=range of wall thickness

From equation (3), the range of wall thickness is defined:

$$\Delta\omega \leq 4.83^{mm} \quad (0.19 \text{ in.}) \qquad (4)$$

and equation (4) is one of the criteria one should follow in the process of sizing members. (0.1 in. $\leq \omega \leq$ 0.3 in.)

Temperature measurements:

Data of various sources are complied and shown in figure 1, taken at different locations, altitudes, seasons, and enviroments. Time-derivative of ambient temperature data of figure 2 taken in high altitude on clear days are considered representative for the 25-M telescope design. Data on vertical temperature difference on telescope structure was only for reference since none of these installations are engineered specifically to reduce the thermal gradient effect of the telescope. Hence data for the daytime period is meaningless. The relatively large nighttime temperature difference of Tucson's measurement is not well understood. More measurements are planned for the future in order to verify the $\Delta T=2^{o}c$ used in this memo.

The 65-M design data is taken from S. v. Hoerner's 65-M report no. 37. This data is condensed from measurements on telescopes in Green Bank, Sugar Grove, and Tucson. This data represents 95% of all clear, calm days used in thermal analysis of the exposed telescope.

Brazilian data was derived from one 36-hour period measurement of ambient air and metal temperature of the 13.7-M telescope within a 22-m radome constructed by ESSCO. Data was taken on June 1, 1972. Six fast-response thermistors were mounted on various parts of the structure and on both sides of the radome. The blower and heater inside the dome were turned on between 0900 and 1200 hours to rid of the dew condensation, with inside temperature 2-3^{o}c higher. The effectiveness of the blower is somewhat limited because the space between the rim of the dish and the radome is small. Both the heater and the blowers are on the ground level.

The Tucson temperature measurements were taken continuously between the months of January and February of 1976, covering the ambient air temperature and metal temperature on the telescope. With the 24-day recordings, about six days with rain, four days with max. ambient air temperature variation larger than 13^{o}c, of which only one day had greater than 18^{o} c. For ΔT, a smoothed out curve of that particular day was used. The door was in open position for the whole day. For $\dot{T}$, a 95% curve is adapted.

Telescope performance in a 24-hour period:

With reference to the data of figure 1, it is clear that air circulation is needed in order to reduce the vertical temperature difference of the structure. The curve of ΔT in figure 2 is adapted, showing a 12-hour period when the door is closed and another 12-hour period with the door opened during a calm night. Preliminary measurements at high altitudes show that temperature gradient is about 2^{o}c during a calm evening. Preliminary designs on air circulation show that a gradient of 3^{o}c inside the astrodome is feasible during a sunny day.

It is planned to obtain more measurements on vertical temperature difference inside an existing open dome on Mauna Kea during the nights. These measurements will supercede the 12-hour portion of $\Delta T=2^{o}c$. Presently, we can consider it acceptable for the preliminary study.

Table 2 listed the surface error due to the thermal effects over a 24-hour period.

TABLE 2 - Surface error due to temperature difference and time derivative of ambient air temperature in a 24-hour period on a typical calm, clear day

hour	$\Delta T(^{o}c)$	$x5\mu m/^{o}c$	$T\ ^{o}c/hr$	$X\ 8\ \frac{\mu mhr}{^{o}c}$	thermal surface error (μm)
18	2.1	11	2.0	16	19
19	2.0	10	1.5	12	16
20	2.0	10	1.1	9	13
21	2.0	10	1.0	8	13
22	2.0	10	1.0	8	13
23	2.0	10	1.0	8	13
24	2.0	10	1.0	8	13
1	2.0	10	1.0	8	13
2	2.0	10	1.0	8	13
3	2.0	10	1.0	8	13
4	2.0	10	1.0	8	13
5	2.0	10	1.0	8	13
6	2.0	10	1.0	8	13
7	2.0	10	1.0	8	13
8	2.0	10	1.2	10	14
9	2.1	11	1.5	12	16
10	2.5	13	2.0	16	21
11	3.0	15	3.5	28	32
12	3.0	15	5.7	46	48
13	3.0	15	5.7	46	48
14	3.0	15	4.3	34	37
15	3.0	15	2.1	17	23
16	3.0	15	1.2	10	18
17	2.6	13	1.4	11	17

Table 3 listed the limiting thermal errors allowed for different wavelengths, assuming all other error contributions remain unchanged. For $\lambda=1.2^{\mathrm{mm}}$, the limiting value is $29^{\mu\mathrm{m}}$ rms. The last column of Table 2 shows the telescope cannot operate at $\lambda 1.2^{\mathrm{mm}}$ between 1100 to 1500 hours, with surface error larger than $\lambda/16$. Similarly, for $\lambda 2.0^{\mathrm{mm}}$, the limiting value is $104^{\mu\mathrm{m}}$ rms, indicating that the telescope can operate at $\lambda 2.0^{\mathrm{mm}}$ all the time.

Projecting into the future, if improvements in the manufacturing technique for the surface plate will reduce the error to 25 μm rms, the subreflector to 20 μm rms, and possibly reduce the measurement error to 15 μm rms, then the limiting thermal error for the backup structure is 19 μms, meaning the telescope can observe $\lambda 0.8^{\mathrm{mm}}$ 75% of the time.

If the loss of the observing time during the day should be considered important, heating elements can be arranged to yield a smoother rise and fall of the inside temperature of the dome, reducing the maximum of T in figures 1 and 2.

TABLE 3. Performance of the telescope, with limiting thermal error in circles for various wavelengths

	Present design goal				Future	
	$\lambda 1.2^{\mathrm{mm}}$		$\lambda 2.0^{\mathrm{mm}}$		$\lambda 0.8^{\mathrm{mm}}$	
Surface Plates	62		62		38	
Manufacture		40		40		25
Gravity		12		12		12
Setting		15		15		15
Measuring		40		40		15
Thermal		16		16		16
Wind		1		1		1
Panel Structure	7		7		7	
Manufacture & gravity		7		7		7
Thermal		2		2		2
Wind		1		1		1
Backup Structure	33		105		25	
Assembly & gravity		16		16		16
Thermal		㉙		(104)		⑲
Wind		1		1		1
Subreflector	25		25		20	
Manufacture & gravity		25		25		20
Total Error (μm)		75		125		50

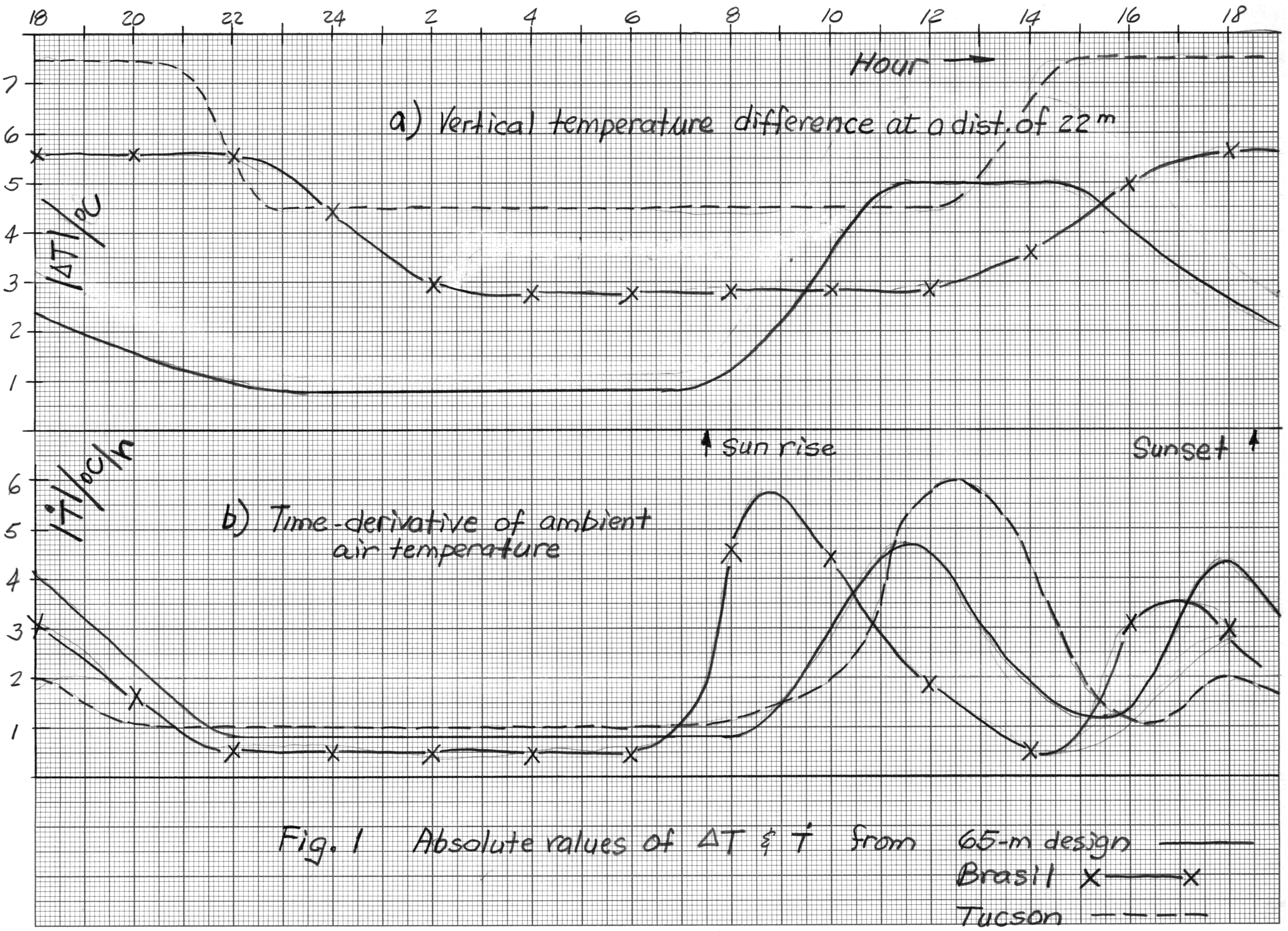
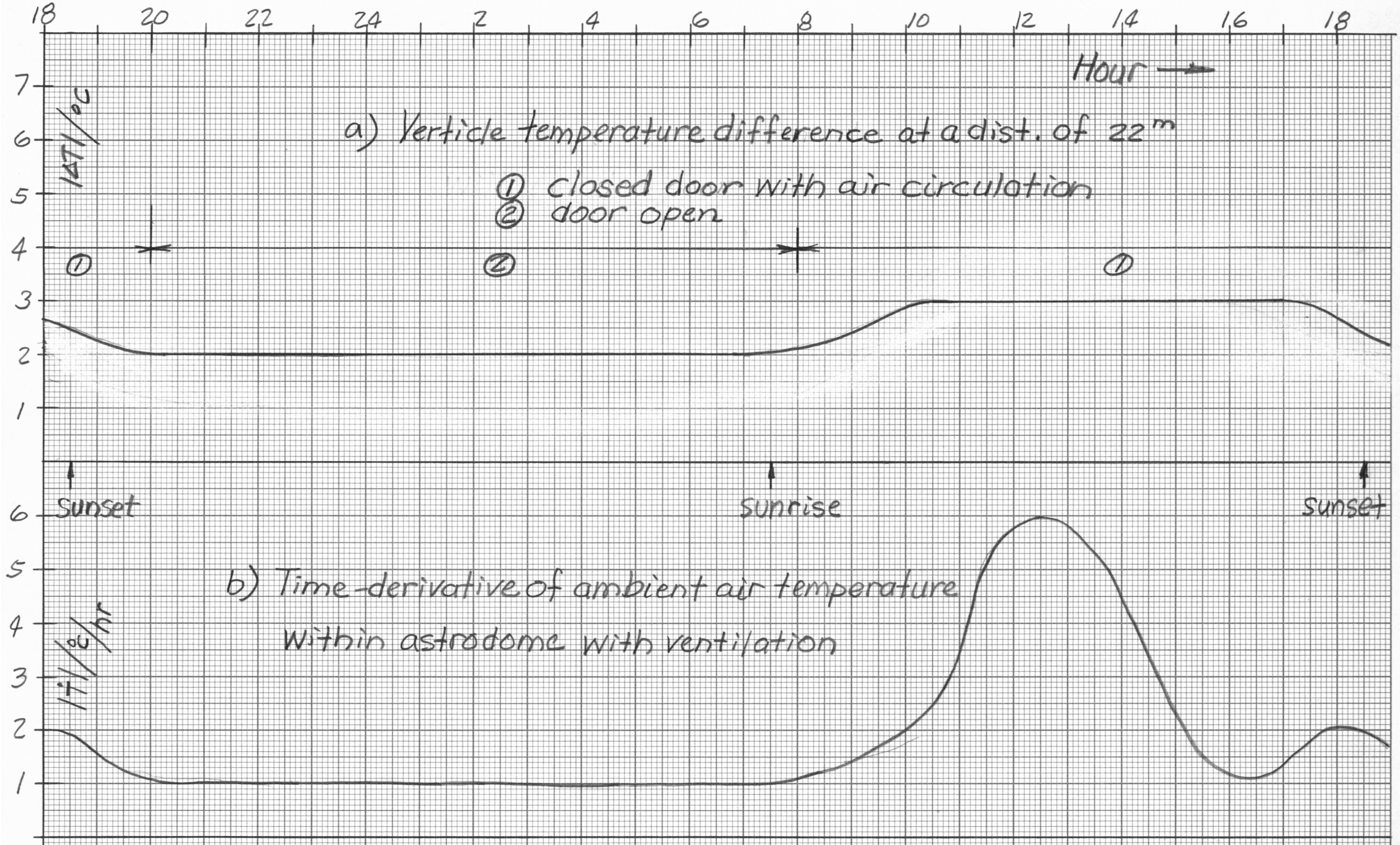


Fig. 1 Absolute values of ΔT & Ṫ from 65-m design



a) Verticle temperature difference at a dist. of 22^m

① closed door with air circulation
② door open

b) Time-derivative of ambient air temperature
Within astrodome with ventilation

Fig 2 Absolute values of ΔT & $\dot{T}$ for the 25-m design