Temperature Measurements On BIMA 6-m Antennas—Part I: Backing Structure

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Abstract

Measurements have been made of the temperature distribution in the antenna backing structures on the 6 m diameter antennas of the BIMA Array at Hat Creek. 32 thermistors were distributed around the backing structure, and on one panel, and were monitored under varying conditions. Significant gradients were found between the front and rear of the backing structure, across the structure, and radially. These gradients produce distortions of the primary reflector surface that result primarily in focusing or pointing errors. The time scales of the temperature changes are short enough to make focusing and pointing corrections of limited effectiveness. Installation of reflective sunshades and fans together reduce the effects by a factor of 2-4. For the BIMA antennas these simple controls reduce the thermal effects to a tolerable level, but for the mmA the effects are larger then allowed for by the specifications. Careful design could reduce the problem, but examination of other materials such as CFRP is clearly warranted.

1 Introduction

Distortions in the shape of an antenna due to temperature gradients are relatively easy to determine using standard finite-element structural models, if the temperature distribution is known, but it is much harder to calculate what the actual temperature distribution will be during normal operation. Greve ***et al.*** [1][2] have made some successful models of the thermal behavior of antennas under varying conditions, but there are still enough uncertainties that further experimental results are desirable. Gradients in temperature of order 0.1 C m^{-1} or less are important for a high precision millimeterwave antenna. Such variations are difficult to predict, but can be measured if care is taken in the instrumentation.

All parts of the antenna, including the mount, main reflector backing structure and panels, and secondary reflector and support, need to be analyzed to determine the effects of temperature on pointing and surface accuracy. In this memo, only the effects in the main reflector are studied. Absolute temperature changes and thermal gradients cause pointing and focus errors, as well as degradation of the surface figure [3]. Some distortions may be compensated for by repointing or refocusing. This may be done by checking the pointing and focus radiometrically, in which case the frequency of calibration needs to be less than the time scales of the thermal changes. Alternatively, separate instrumentation could be used to determine the temperature gradients and the structural changes calculated in real time. Careful experiments would be required to demonstrate a systematic correlation between the temperature changes and the antenna errors. Instrumentation could also be used to measure the distortions directly.

Ideally, the antenna should be temperature independent but that requires the use of expensive low-expansion materials such as carbon-fiber-reinforced-plastic (CFRP) or Invar. This study investigates how well a steel structure behaves with no thermal control, and with simple controls (*i.e.*, sunshades and fans). At this point no attempt has been made to correlate the thermal measurements with pointing or focus, but some experiments have been planned.

The thermal effects will be evaluated in terms of the BIMA antennas and projections made for the mmA

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antennas. For the mmA antennas the measurements are probably a good guide for a similar construction of steel. If CFRP is used then the temperature distribution could be significantly different because of the different thermal conductivity and specific heat. The emissivity would be similar, since similar paint could be applied.

2 Antenna Structure

The backing structure (BS) of the antenna (Figure 1) is fabricated from square cross-section steel members, welded into plane trusses with tangential cross bracing. At the center is the receiver cabin that forms a rigid conical shell on which the BS is mounted. Protection from solar heating on the rear of the BS is provided by trapezoidal panels of insulation (~50 mm thick, R-Value = 11) with a reflective aluminum face-sheet on the outside. The shades are clamped to the BS with rubber pads between the shade and the steel members so that they are thermally isolated and have a gap to allow exchange of air between the inside and outside of the BS. Four fans are mounted in the BS, forcing a tangential airflow to minimize temperature inhomogeneities.

There are 84 cast aluminum panels supported on the front of the BS by steel studs. The fronts of the panels are machined with a diamond-tipped fly-cutter, while the rear surface is the rough, matt finish typical of casting.

3 Instrumentation

All the measurements were made using YSI 44016 Precision Thermistors (YSI, Inc.) with a specified interchangeability of ±0.2 C. The thermistor elements were potted in a section of copper tube using thermally conductive epoxy (Thermalloy Thermalbond 4952). One end of the tube was crimped flat and drilled for a mounting screw.

Some measurements were made through the Array Telemetry System that can monitor up to 24 thermistors, but most of the measurements were made using an IBM AT computer as the data logger. Two PCLabs PLC812 data acquisition cards were used allowing up to 32 sensors to be monitored. Figure 2 shows a schematic of the circuit used to supply and monitor the thermistors. The reference voltages come from the ADC outputs on the cards and can be varied up to 5 V. The voltages on the thermistors are monitored on the 12-bit, ±5 V DAC inputs. At 20 C this gives a temperature resolution of about 0.04 C when a 5 V reference is used. The reference voltage may be varied to change the dissipation in the thermistor, but since the self heating of the sensors is not a problem when they are attached to substantial supports such as the BS the reference was kept at 5 V to give the highest possible resolution.

Before the sensors were mounted on the telescope they were attached to an aluminum plate to check how well they matched each other. Monitoring over a two-day period yielded an rms variation of 0.023 C over 24 sensors. The maximum deviations from the mean were -0.140 C to +0.076 C, well within the manufacturer's specification of ±0.2 C. When the sensors were left in free air in the lab, all within less than 0.5 m of each other, the rms variation was about 0.2 C.

4 Thermistor Locations

A set of 32 sensors was mounted on the BS of Antenna 7 in June 1933. These were taped on using duct tape, and had a coating of GE Thermal Grease to provide good contact with the struts of the BS. A layer of aluminum tape was also used to minimize radiative heating and cooling of the sensors. Figure 1 shows the distribution of the sensors on the BS. Eight sensors were placed on each of the upper, lower, right and left ribs with four on the front and four on the rear of each.

A single sensor was attached to the back of a surface panel near a mounting stud and a sensor was located near the other end of the stud on the BS.

5 Measurement Results

The results reported here cover three sets of readings, each taken over a period of about six days. The first set was started on the 11th of June, the second on the 23rd of June after some sunshades had been removed and the fans turned off, and the third was started on the 29th of June during which the fans were restarted with the sunshades still off.

5.1 11th June

During this period the weather was hot and clear. There were sunshades installed on the BS and the circulation fans were turned on. Normal observations were taking place so that the antenna was pointing in different directions in the sky.

Figure 3*a* shows the average temperature in the BS. It follows a regular diurnal cycle over a range of about 25 C. During the day the rms variation in temperature among the thermistors typically reaches 0.8 C, while during the night a value of around 0.2 C is observed.

Figure 4 shows the temperature differences between different parts of the antenna structure. For example, the top-to-bottom difference is the difference between the average of the eight sensors on the truss on the top of the backup structure and the average of the eight sensors on the truss on the bottom side. The most extreme excursions are in the panel, as expected since the panel has only moderate solar reflectivity and is loosely coupled with the BS. Differences between other parts of the structure typically have extreme values of about 1 C. For left-to-right and top-to-bottom differences this is an average gradient of about 0.25 C m^{-1}, and for front-to-back differences it is about 1.3 C m^{-1}.

5.2 23rd June

Again, clear, sunny days. Two sunshades were removed from each side of the ribs that had thermistors mounted on them and the fans were turned off. The antenna was not moved during this period. Temperature excursions were similar to those of the 11 June data but the rms of the BS was higher by as much as a factor of three or four.

Figure 3*b* gives the average and rms BS temperatures. While the average is similar to that for the 11 June data the rms is higher by a factor of three to four.

Difference temperatures are shown in Figure 5. Again the panel shows the largest differential, but there is also a significant difference between other parts of the antenna, notably the left-to-right measurements. The top-to-bottom difference is not as large but has a bias in the negative direction, showing that the top of the structure is *cooler* than the bottom. Although the sign is surprising, the stratification may be expected as the antenna was pointed at the horizon during the measurements. Gradients are up to about 1.5 C m^{-1} top-to-bottom, 0.75 C m^{-1} right-to-left, and 2.6 C m^{-1} front-to-back.

5.3 29th June

Conditions were the same as for the 23 June data, except that the fans were restarted in the afternoon (similar to a situation with clear, windy conditions). Two days' of data were taken. Figure 3*c* shows the average and rms temperatures over the period. Although the data are not unambiguous because of the short time, there is some evidence that turning on the fans reduces the temperature gradients, even with the sunshades removed. The difference temperatures in Figure 6 also show some improvement compared to no fans or sunshades.

6 Discussion

Clearly the sunshades and fans make a noticeable difference to the thermal gradients within the antenna backing structure. Improvements are seen both in the daytime and the nighttime, though more obviously during the day. Typically the reduction in the temperature gradients is a factor of two to four when the sunshades and fans are used. It is not clear how much of the improvement is due to the fans and how much is due to the sunshades, but the data of 29 June suggest that the two may be similarly effective. (Actually, the combined effect is probably greater than the sum of the individual improvements.)

The fans have a specified displacement of about 85 m^{-3} min^{-1} (3 000 scfm). If this flow is confined within the cross-sectional area of the fan the air speed is about 15 m s^{-1}, but if it is spread out through the whole cross-sectional area of the BS the flow is about 1 m s^{-1}. These limits give forced convection heat extraction rates of about

20-70 W m^{-2} K^{-1} [4]. Typically, the heat removal by natural convection is ~2-4 W m^{-2} K^{-1} and radiative losses are comparable. If average values of say 50 W m^{-2} K^{-1} and 8 W m^{-2} K^{-1} are taken for forced convection plus radiation and natural convection plus radiation respectively, it may be seen that the improvement is about a factor of six. This is somewhat larger than the improvement in the temperature uniformity observed.

The effects of the temperature on the surface accuracy, pointing, *etc.* will depend on the precise temperature distribution. Figures 7 and 8 show how the temperature varies as a function of radial distance along the trusses for some typical conditions. For each of the data sets there is a set of graphs covering a 24-hour period in two hour intervals. When the sunshades and fans are used the backing structure temperature is very uniform during the night (from about 10 p.m. to 6 a.m.), the maximum differences being less than 1 C. During the morning (6 a.m. to noon) the antenna starts to warm up, starting at the rim so that a gradient develops between the center and edge of the dish. At the same time some difference arises between the front and rear of the backing structure. By the middle of the day the radial gradient is reduced but the front-to-back difference is still significant. There is also some scatter in the temperatures that is not very systematic. In the afternoon the temperature falls, slightly faster at the edge than the center.

Without the sunshades the temperature gradients are more dramatic. Nighttime temperatures are still fairly uniform, though there is still an appreciable difference between the front and the back of the structure (of order 1 C) and an observable radial gradient. In the morning a radial gradient, increasing towards the edge, is evident. This can be as high as 2 C m^{-1}, and may be due either to the lower time constant of the central cone, or to the influence of the receiver cabin temperature control. The front-to-back difference is on the order of 1 C.

An unexpected feature is the discontinuity that arises at the outer section of the dish where the temperature drops significantly. It may be because the structure can lose heat through the edge as well as the back and front surfaces.

6.1 Estimation of Thermally Induced Errors

Some approximate analytical expressions relating the temperature gradients to structural changes have been derived [3]. In evaluating them the following values were assumed:

Antenna:

Primary diameter D	6.00 m
Focal length, f	2.40 m
Focal ratio, f/D	4.00 m

Backing Structure:

Material	Steel
Tube thickness	3.2 mm

Panels:

Material	Aluminum
Thickness	6-12 mm
Typical panel size	0.8 m

Panels: When the temperature changes uniformly, the paraboloidal profile to which the aluminum panels are cut will expand at a different rate from the paraboloid that the steel backing structure is set to. Consequently, a uniform temperature change will induce a surface error. Since the expansion coefficient of aluminum is twice that of steel, a 2 C temperature change is equivalent to a 1 C temperature differential between the panel and BS. Numerically, there will be an rms surface error component of about 0.2 µm C^{-1} for temperature differences and 0.1 µm C^{-1} for uniform temperature changes. Clearly, these are acceptable for the observed differences between the panel and the backing structure of 12 C, and a temperature range of ±25 C.

Front-to-Back Gradient: This type of distribution causes a curvature of the main reflector surface equivalent to a change in focal length, possibly with some residual surface error. For a 1 C difference the change in focal length is about 0.3 mm, which is equivalent to a surface error component of about 40 μm (rms). This could be compensated by moving the secondary, but the time scales of the changes are on the order of 0.5-1 hr so the focus could change significantly between focus calibrations. A further complication is that the secondary support struts are directly attached to the rim of the primary so that when the dish focal length decreases the secondary is pushed further out, exacerbating the effect.

For the BIMA antennas the above errors are probably acceptable, but they could be a problem for the mmA antennas, even if fans and sunshades are used to keep the difference down to 0.3-0.5 C. It is not obvious that this could be passively compensated by a different secondary mounting design.

Radial Gradient: A radial gradient also gives a change in focal length, amounting to approximately 0.1 mm for the worst cases measured here. The associated equivalent surface error with no refocusing is about 12 μm. More typically these values would be less than half that. If refocusing is allowed the error is reduced to 1 μm in the worst case for a linear radial gradient. Since the forms of the distortion induced by front-to-back gradients and radial gradients are similar they should be added arithmetically rather than in quadrature. From typical results such as shown in Figure 8 it is found that the two effects have opposite signs and will partially cancel each other, at least in the cases studied. It is possible that for some cases the effects could add to produce a worse effect.

Lateral Gradient: Lateral gradients may be about 2 C across the dish. The corresponding pointing shift will then be about 0.4 arcsec which is negligible for the BIMA antennas, but will be a significant part of the mmA antenna pointing budget. To first order there is no effect on the surface accuracy.

Non-systematic Variations: There are variations in the temperature distribution which are not very systematic during the day. It is hard to calculate the results of these distributions without resorting to detailed structural models, but if the temperature gradients are similar to those discussed above they can be expected to have an effect of similar magnitude as the uncompensated errors of the systematic variation. Gradients of order 1 C m^{-1} may be seen in the daytime results even when the fans and sunshades are on, so error contributions in the 10-20 μm range are likely.

Time Constants: Time constants for the backing structure and the panels are predicted to be about 0.3 hr and 0.4-0.9 hr respectively. This is commensurate with the timescale of variations seen in the data. During the night the short time scales ensure that the temperatures can become uniform quite quickly, but during the day the structure will be affected by changes in the thermal environment, such as partial cloud cover or changes in pointing direction. The magnitude of the changes is significant, but the time scales are too short to be calibrated out completely by observing astronomical sources.

6.2 *Comparison With Thermal Error Budgets*

For the BIMA antennas an allowance of 15 μm is made for the thermally induced surface error. For the mmA antennas [5] the backing structure has an allowance of 4 μm for gradient induced errors and 4 μm for absolute temperature induced errors. No specific budgets have yet been given for thermal effects on pointing. The calculations reported above are approximate—comparisons with some finite-element-models were within a factor of two—but with this in mind the following comments may be made.

The largest errors are from uncompensated focus changes resulting from front-to-back gradients. With no sunshades or fans this is an error of about 100 μm, which is halved when the sunshades and fans are on. Most of this can be removed if the secondary is refocused, but there are probably still residual errors from small scale temperature variations which are 10-20% of this or 10-20 μm with no thermal controls, 5-10 μm with fans and sunshades. In absolute terms, the deflections will be about 35% larger for the larger mmA antennas if the total temperature range is the same (but *larger* if the *gradients* remain the same). For the BIMA antennas the thermal controls bring the errors within specification, but for the mmA the specification is exceeded.

An allowance of 4 μm each is made for absolute and gradient temperatures for the mmA antennas [5]. The extreme values estimated above for the BIMA panels are ~2.5 μm in both cases which is quite acceptable. Scaling to a larger size of 1 m for possible mmA panels gives 4 μm, within specification.

7 Conclusions

Measurements made on the BIMA 6-m antennas show that the temperature gradients in a steel structure give rise to significant distortions of the primary reflector. At night the temperatures are sufficiently uniform that the required antenna accuracy can be maintained, but during the day the temperature gradients are large enough to deform the structure and reduce the antenna efficiency. For the most part these distortions are mainly manifest as focus and pointing errors but the rate at which they change is fast enough to make real-time correction only partially effective. The use of fans and sunshades reduces the thermal gradients by a factor of 2-4 (and this could possibly be increased with further thermal design) which results in acceptable performance for the BIMA antennas, but which falls short of the specifications for the mmA antennas.

Since the calculations used here are approximate, the conclusion that a steel structure will not meet the mmA specifications is not unequivocal, but it warrants serious investigation of alternative materials. A CFRP structure could give a larger margin of safety on the thermal performance and this, along with its other advantages, makes it a material worth considering. In making full use of the low-expansion properties of CFRP, careful attention has to be paid to the interface between it and the steel supporting structure. Suitably reflective surface treatments have to be demonstrated to avoid the large temperature gradients which would arise from solar absorption by the dark material, nullifying the low expansion coefficient advantage.

8 References

[1] A. Greve: "Thermal design and thermal behaviour of radio telescope structures", IRAM Int. Report, 1992.

[2] A. Greve, M. Dan, and J. Penalver: "Thermal behavior of millimeter wavelength radio telescopes", *IEEE Trans. Antennas and Propagat.*, vol. 40, no. 11, pp 1375-1388, November 1992.

[3] J. W. Lamb: "Thermal considerations for mmA antennas", *mmA Memo Series*, no. 83, May 1992.

[4] E. C. Guyer: *Handbook of Applied Thermal Design*, New York: McGraw-Hill, 1988.

[5] J W Lamb: "Proposed surface error budget for mmA antennas", *mmA Memo Series*, no. 96, May 1993.

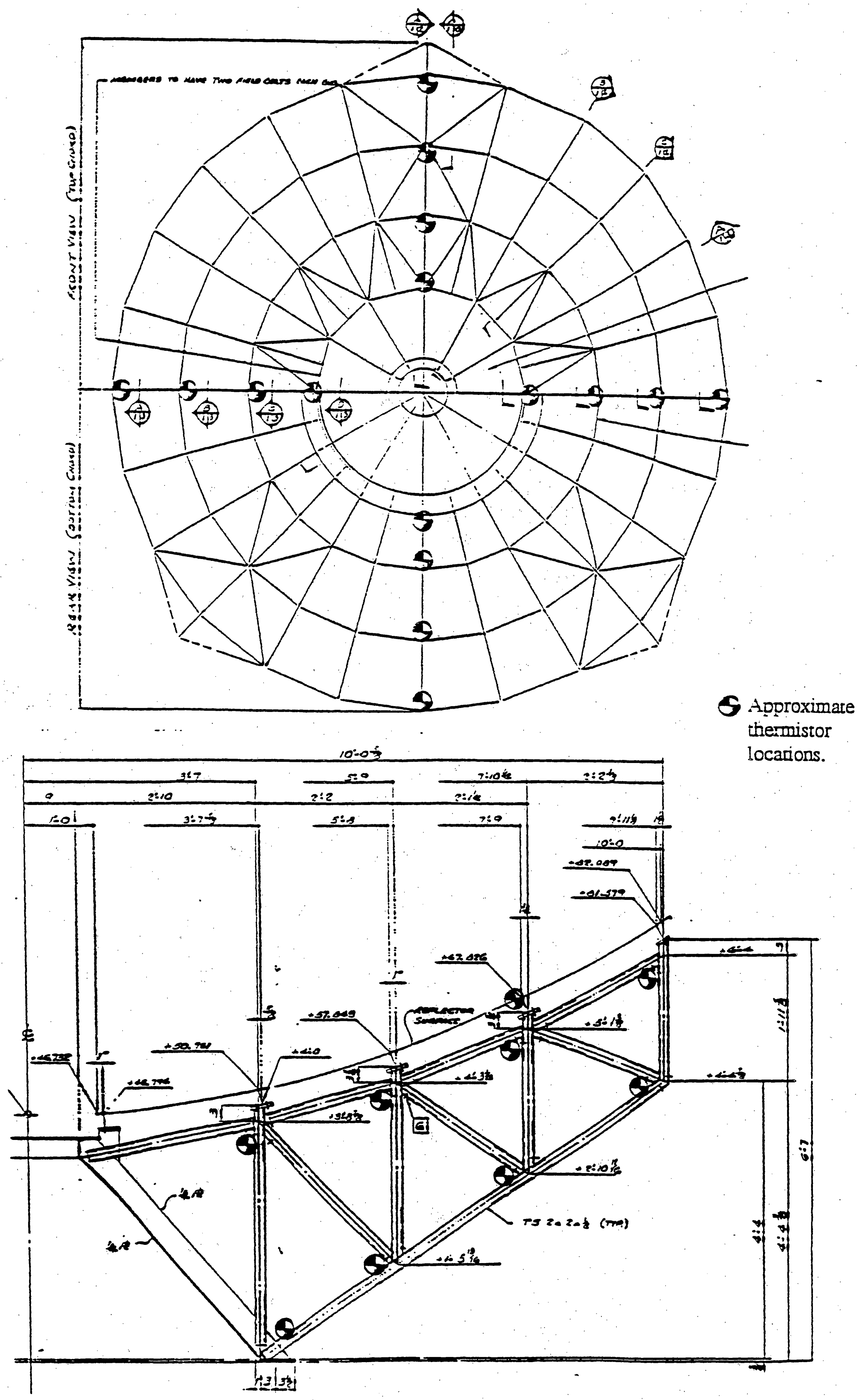

Figure 1. Drawing of backing structure truss showing location of thermistors.

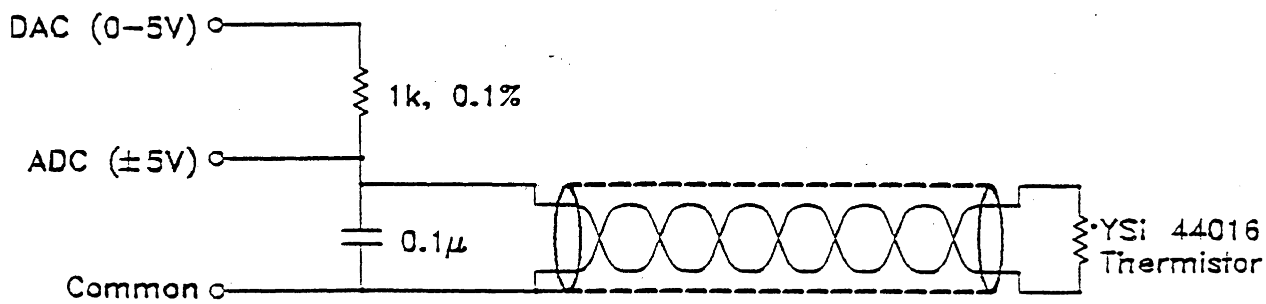

Figure 2. Circuit used to supply current to thermistors and read voltages.

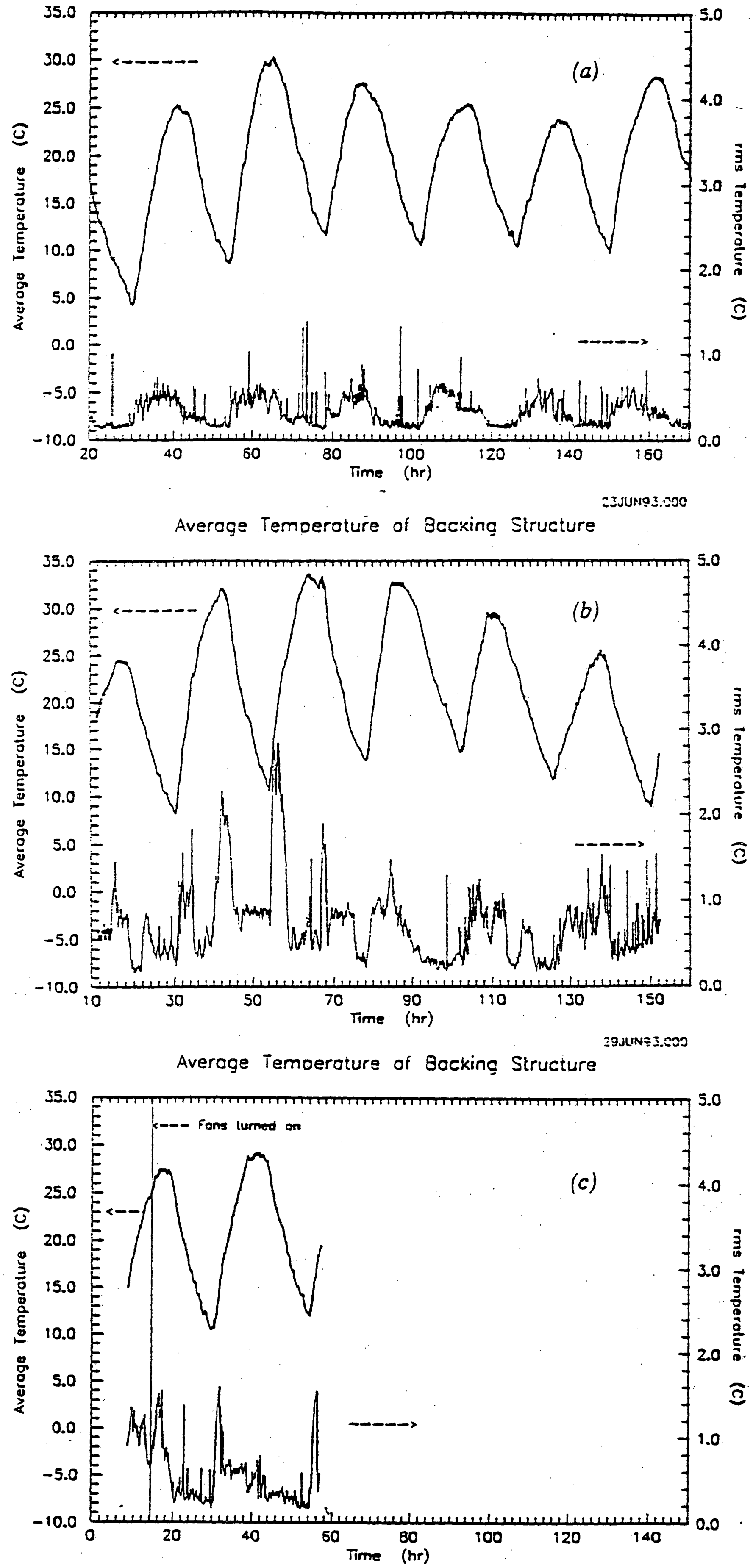

Figure 3. Average temperature in the backing structure, and rms variation of sensor readings from the mean.

(a) 11th June 1993, fans and sunshades on.

(b) 23rd June 1993, fans and sunshades off.

(c) 29th June 1993, fans on and sunshades off.

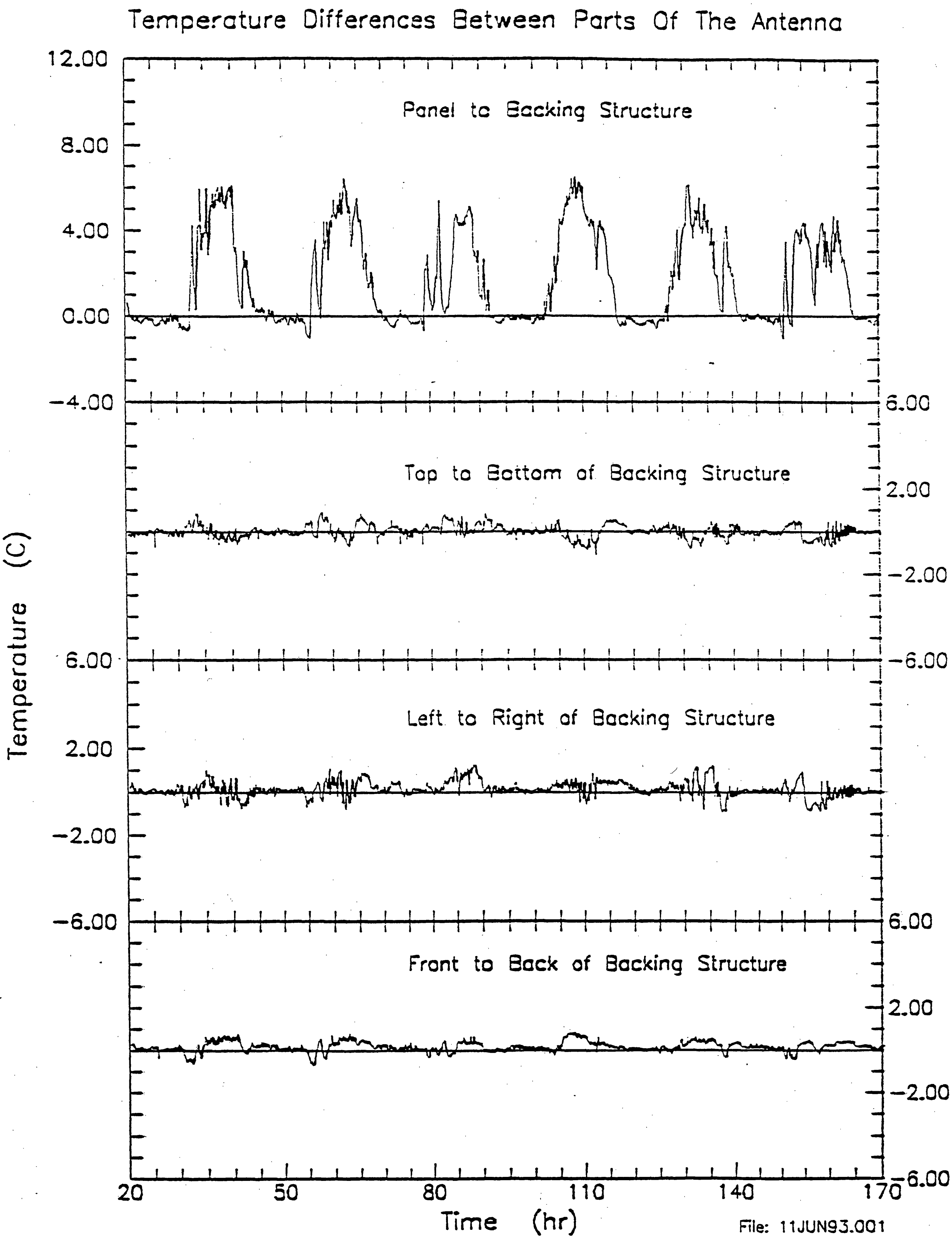

Figure 4. Differences between parts of the BS for 11th June 1993 data, fans and sunshades on.

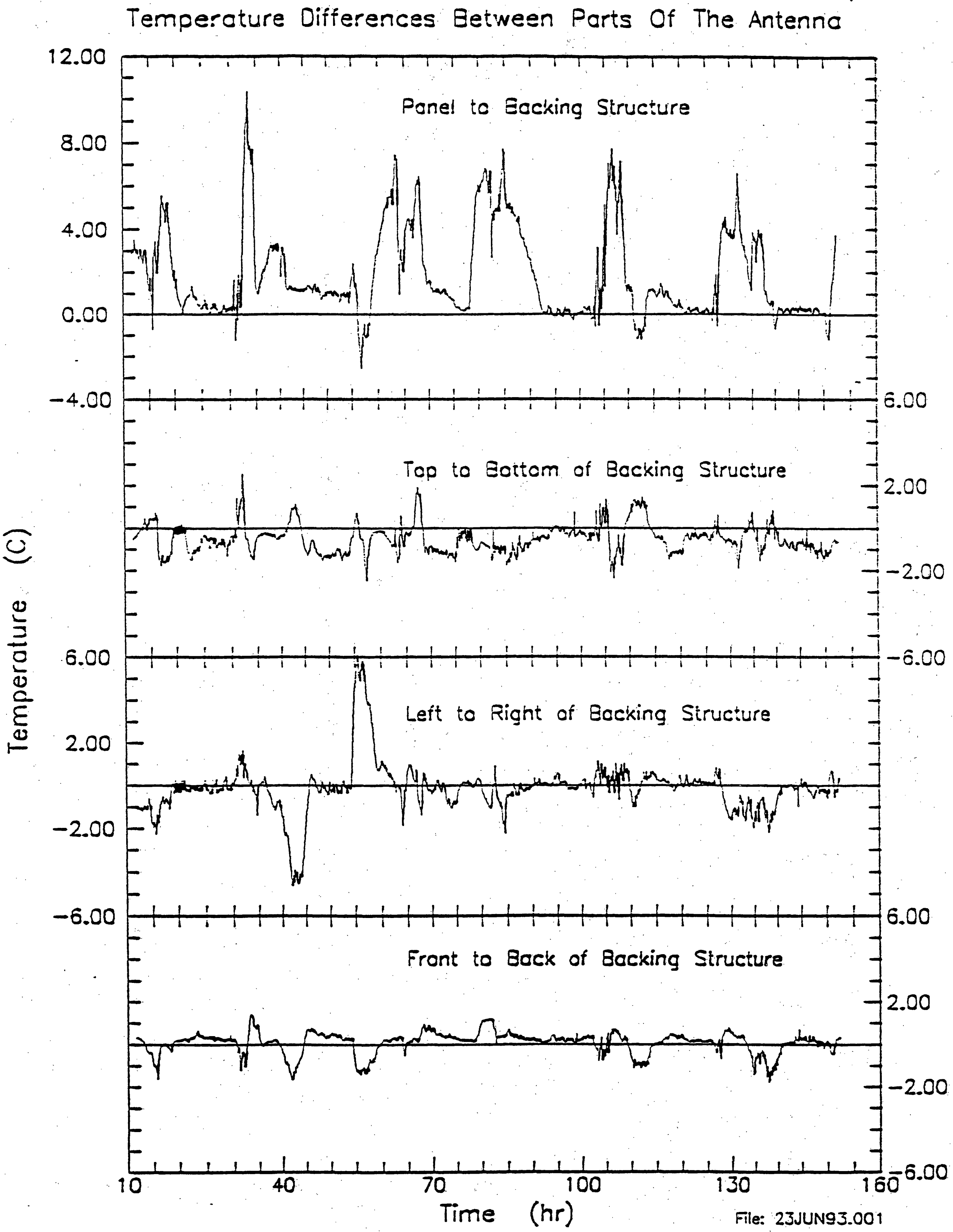

Figure 5. Differences between parts of the BS for 23rd June 1993 data, fans and sunshades off.

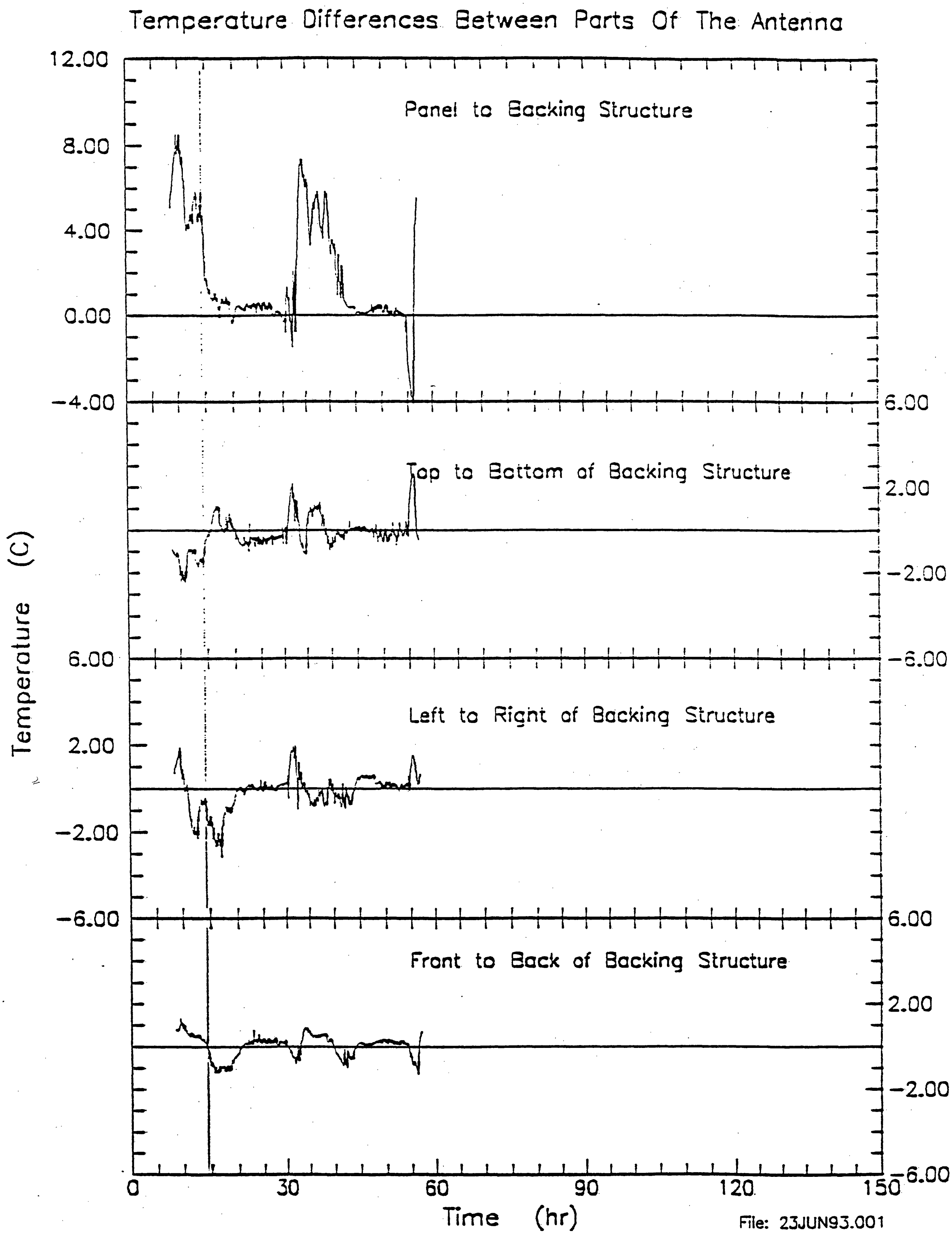

Figure 6. Differences between parts of the BS for 29th June 1993 data, fans on and sunshades off.

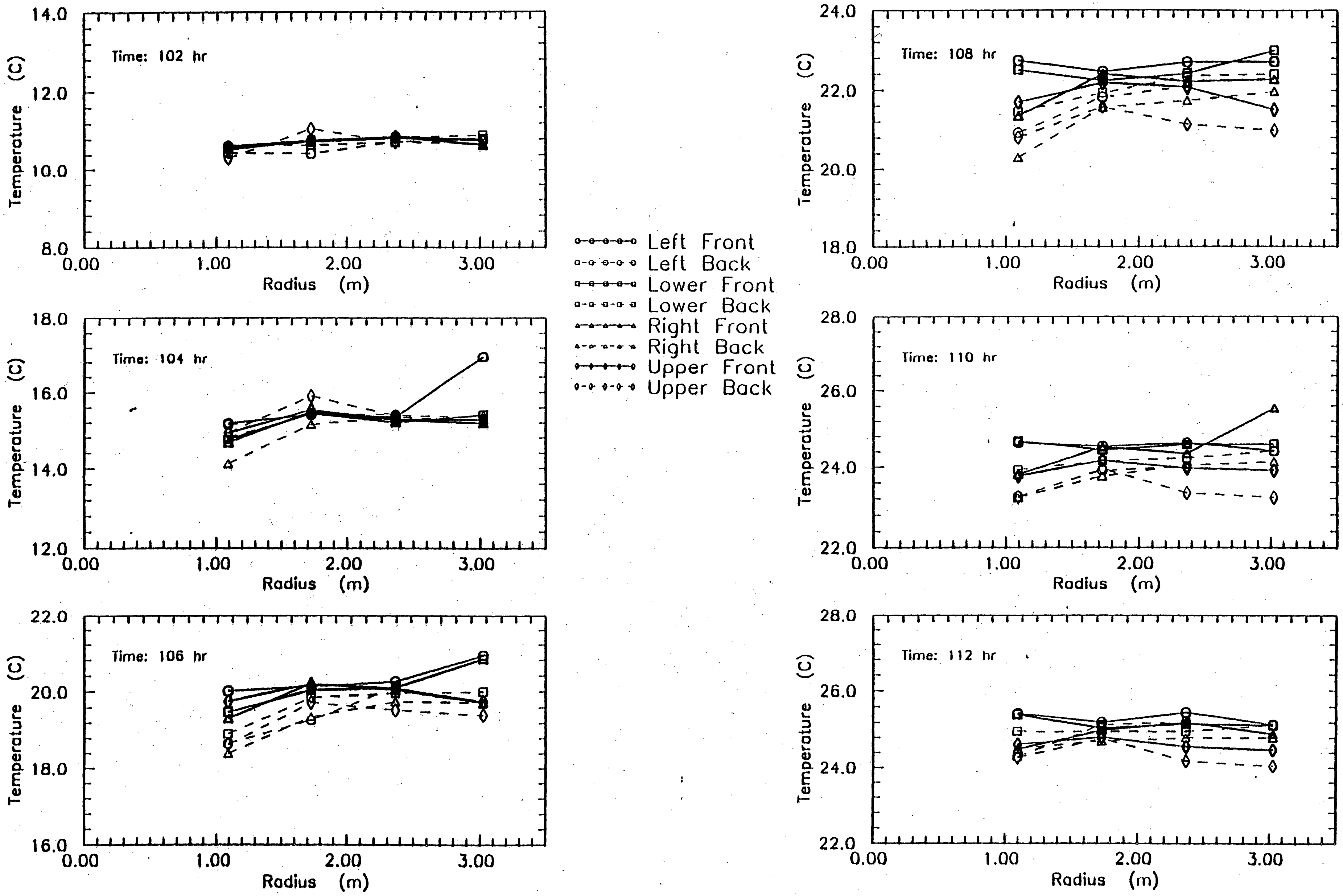

Figure 7. Temperature plotted as a function of radial distance along truss for the four trusses, front and rear. For 11[th] June 1993 data, fans and sunshades on.

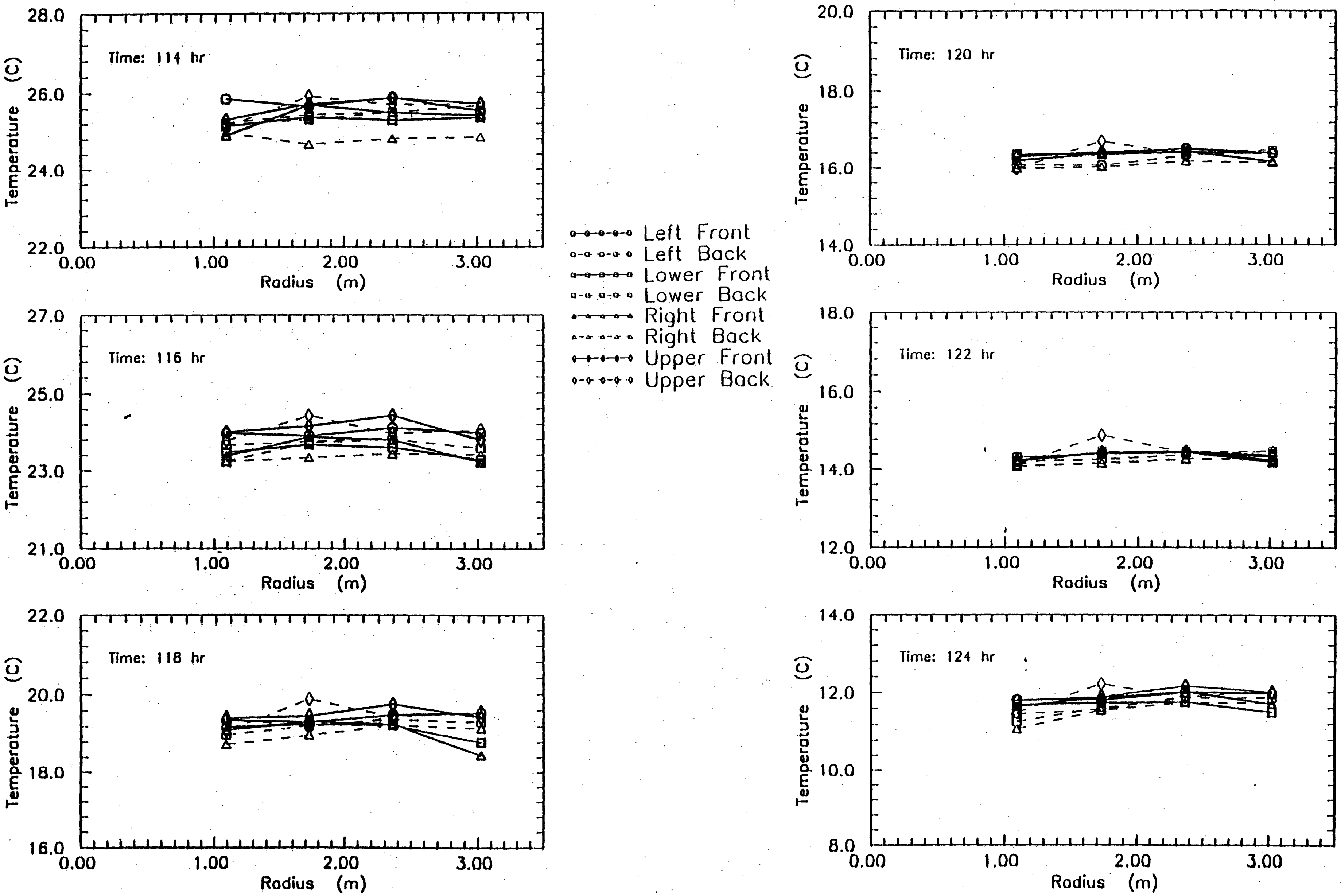

Figure 7. (cont'd)

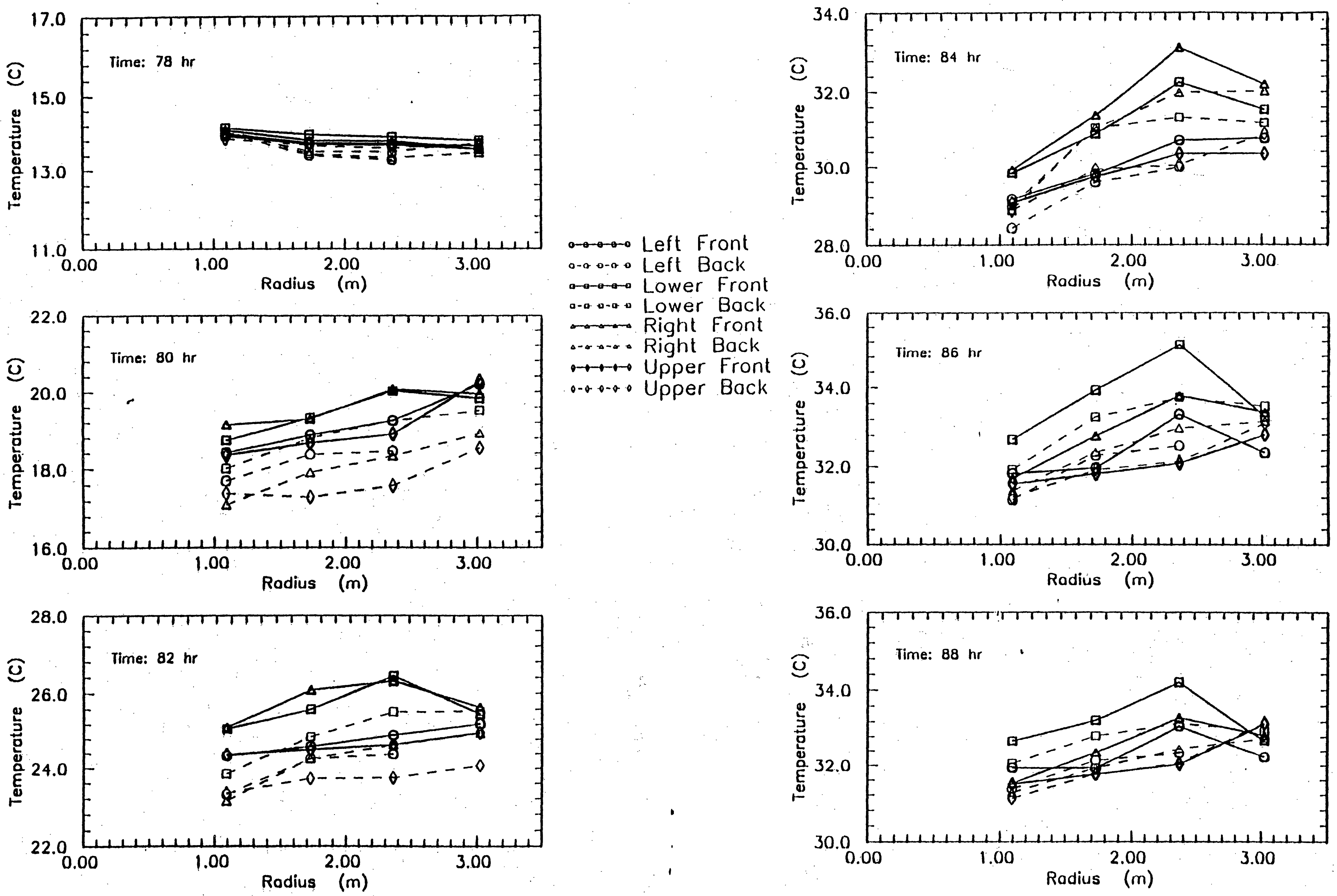

Figure 8. Temperature plotted as a function of radial distance along truss for the four trusses, front and rear. For 23rd June 1993 data, fans and sunshades off.

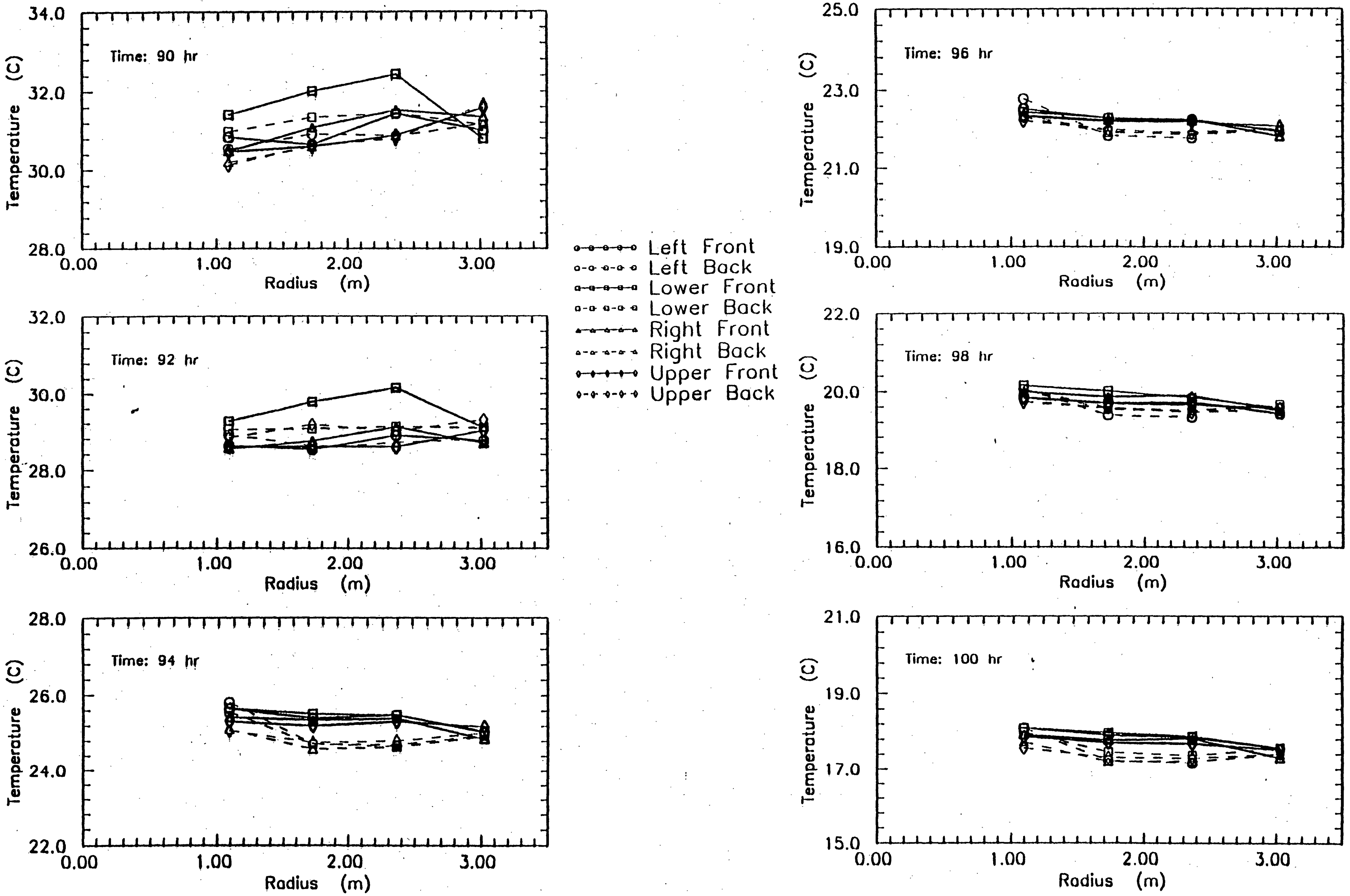

Figure 8. (cont'd)