CORRECTION OF ASTIGMATISM
IN THE 36-FOOT TELESCOPE

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I. INTRODUCTION

Initial observations with the NRAO 36-foot telescope on Kitt Peak revealed that the antenna gain was substantially affected by the ambient temperature. At both high and low temperatures the gain decreased and the beam became elliptical in cross section. It was evident that the optimum telescope focal length not only depended on temperature, but also that the azimuth- and elevation-plane focal lengths had different temperature dependencies. In an effort to understand and correct for these effects, Conklin (1970) installed thermistors on the reflector rear surface and found an empirical correlation of the focal length for maximum gain with both the average ambient temperature and with the radial reflector temperature gradient. The on-line computer was programmed to periodically read the thermistors and refocus the telescope according to the empirical focus equation. The result was a dramatic improvement in both the mean value and, to a lesser extent, in the stability of the telescope gain. However, refocusing can only correct the curvature of field and not the astigmatism produced by the thermal deformations of the reflector. As a result, the beam ellipticity and some gain variations remained. At short wavelengths ($\lambda \leq 4$mm) these effects were still serious and limited the accuracy of observations of point sources. This report summarizes the effort made during the past several years to understand and to correct the residual temperature-dependent astigmatism.

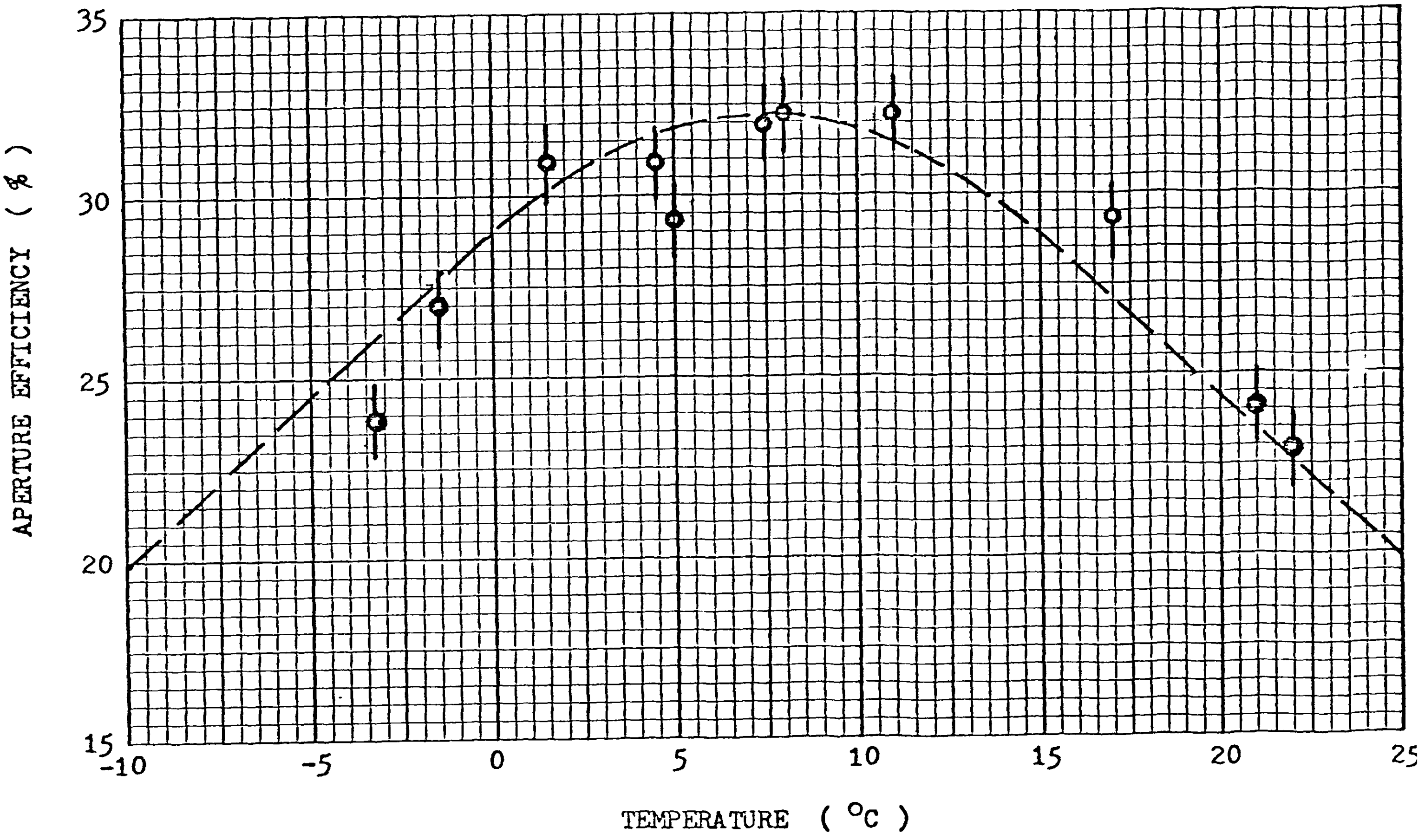
II. INITIAL TELESCOPE PERFORMANCE

The most important parameter of absolute telescope performance is gain. Aperture efficiency is a relative measure of telescope gain at a given wavelength, and here it is a more convenient parameter to use in describing telescope performance. Large diurnal and seasonal variations in the aperture efficiency of the 36-foot telescope were noted at 3 mm wavelength even when the feed horn was focused to receive the maximum possible signal (Conklin 1970). Figure 1 is a plot of aperture efficiency at 3 mm as a function of ambient temperature. Clearly the telescope performance suffered drastically at both high and low temperatures. In addition to decreased gain, the beam cross section became elliptical at extreme temperatures, indicating that large-scale phase errors were the cause of the reduced efficiency. Additional measurements showed that the focus curve was somewhat broadened, and that the azimuth and elevation beamwidths were minimized at different axial foci. This meant that the most important type of phase error was astigmatism - that is, the focal length of the main reflector was different in two orthogonal planes. The difference in the two focal lengths (elevation focus - azimuth focus) is called the astigmatism parameter α, and it is plotted versus ambient temperature in Figure 2. The dashed line fit to the measurements by the least-squares method is given by

$$\alpha = 1.38\ (\pm 0.07)\ \{T - 7.5\ (\pm 0.6)\ ^{\circ}\mathrm{C}\}\ \mathrm{mm}. \qquad (1)$$

Thus at an ambient temperature of 7.5°C there is no astigmatism present. It seems very likely that the dish and backup structure were mated at this temperature in the original fabrication of the telescope. Equation 1 also indicates that the astigmatism parameter increases by 1.38 mm/°C, and the apparently good fit indicates that the astigmatism is a linear function of temperature over the entire range of ambient temperature on Kitt Peak. According to Bracewell (1961), the relative antenna gain η is related to

FIGURE 1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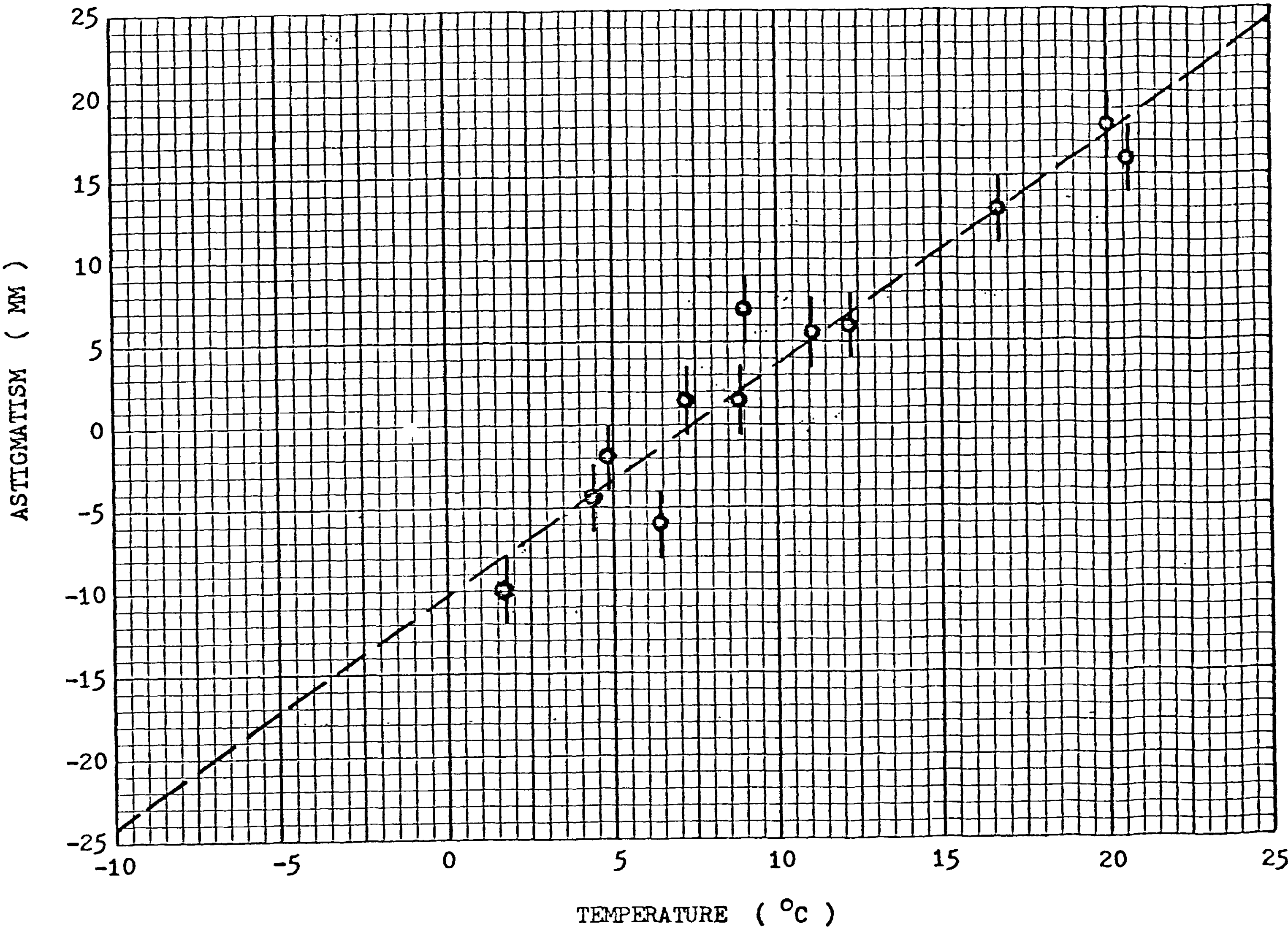
APERTURE EFFICIENCY (%)
TEMPERATURE (°C)

FIGURE 2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ASTIGMATISM (MM)
TEMPERATURE (°C)

the astigmatism parameter α by

$$\eta = \frac{1}{1 + \frac{(\alpha/\lambda)^2}{85}} \tag{2}$$

where λ is the wavelength of observation. Equation 2 is plotted in Figure 1 as the dashed parabolic curve (assuming a maximum aperture efficiency of 32.2 %), and it is clear from the good fit that astigmatism alone can account for the reduced efficiency. Higher order phase errors may exist, but they must be small compared to the astigmatism.

III. PROPOSED REMEDIES

The focal length of the 36-foot telescope was known to vary with temperature, but additionally it was noted that most of the change occurred in the elevation plane, while in azimuth the focal length varied by a lesser amount. Apparently something in the structure was behaving like a bimetallic thermostat and flexing the primary reflector. The first suspected culprit was the steel guy wires which supported the focal point structure (Conklin 1971a). Since the dish is aluminum, it was obvious that the different coefficients of thermal expansion of steel and aluminum would produce a temperature-dependent stress on the reflector. Some tests were conducted to verify this conclusion, but the results were nebulous. In 1971 the steel cables were replaced with rigid aluminum legs (Conklin 1971c). Subsequent measurements showed that they had little effect on the magnitude of the astigmatism, in agreement with rough calculations (Conklin 1971b).

The other obvious bimetallic joint in the structure occurs between the aluminum reflector and the steel backup structure (elevation axle and elevation drive wheel). There is clearly mechanical asymmetry here, too.

The backup structure has a larger span in the elevation plane, and thus one would expect the reflector to be most affected by thermal stress in the elevation plane, in agreement with the observations. A computer model of the telescope structure utilizing the NASTRAN program was constructed to determine the cause of the astigmatism and to evaluate proposed remedies (King 1975). This model consists of linear beam members and two-dimensional plates. Calculations of the effects of gravitational loading were verified by taking strain gage readings on several of the backup struts at different elevation angles. The conclusion of the computer modeling was that thermal astigmatism of the correct sense was indeed predicted, but the calculated magnitude was considerable smaller than the direct observations indicated. Several suggestions were made about how to empirically correct the astigmatism by applying external forces to the reflector through hydraulic cylinders, jack screws, or contact heaters. However, the computer model predicted little improvement in telescope performance with any of these "active" schemes. A "passive" modification of the support structure was proposed by King (1976) which resulted in a large improvement in the astigmatism predicted by the computer model. This remedy involved (1) replacing some of the steel angles in the support structure with aluminum counterparts, (2) removing the extreme elevation plane backup struts, and (3) stiffening the reflector ribs in the elevation plane with aluminum plates and angles. This reduces the thermal stress and redirects it to stiffer points on the reflector ribs. The net effect is a significant decrease in the resulting thermal deformations of the reflector surface. Of course, these modifications also affected the gravitational deformations, and the final design was chosen as a compromise between a thermally stable telescope and a gravitationally stiff one.

IV. STRUCTURAL MODIFICATIONS

The aluminum members needed for the structural modifications were fabricated in the Green Bank shop and shipped to Tucson. From February 14-17, 1977, some 590 kg of steel were removed from and 360 kg of aluminum were installed on the 36-foot telescope, requiring 130 man-hours of labor. Initial radiometric tests showed large residual astigmatism, but this was expected since we had no means of lifting the feed legs during the modifications. Shims were placed under the east and west feed legs, and the proper thickness was found empirically (Ulich 1977) to reduce the residual astigmatism to zero (at an ambient temperature of -4 °C).

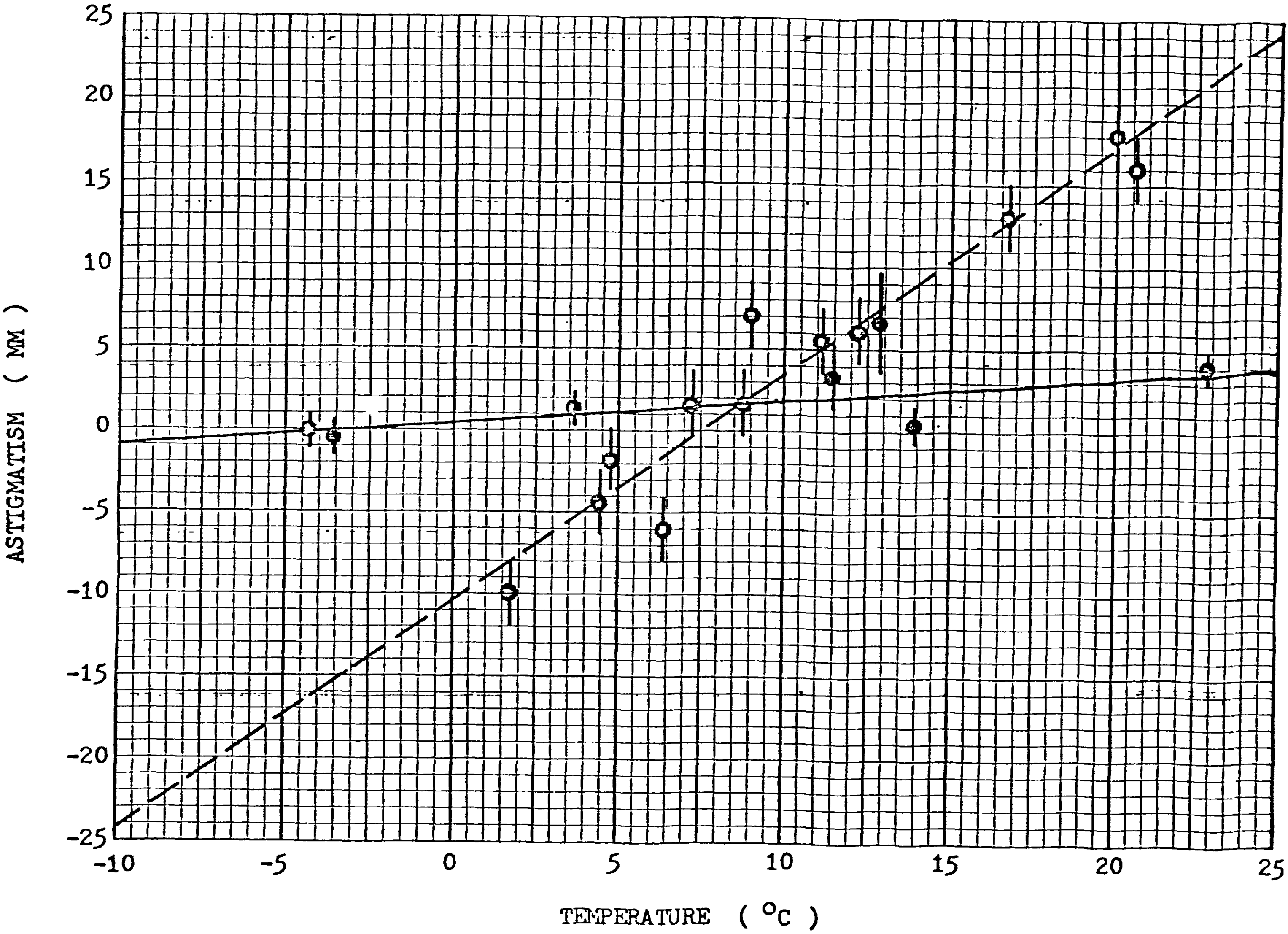
V. MODIFIED TELESCOPE PERFORMANCE

Occasional radiometric observations were made from February,1977 to June, 1977 in order to evaluate the modified telescope performance over a wide range of ambient temperature. Figure 3 is a plot of the measured astigmatism versus temperature. In Figure 3 the filled circles are the new data from the modified structure and the open circles are the original data. Clearly a substantial improvement has resulted, although the astigmatism has not been completely removed at high temperatures. The least-squares line fit is

$$\alpha = 0.14\ (\pm 0.01)\ \{T + 3.1\ (\pm 0.3)\ ^{\circ}\mathrm{C}\}\ \mathrm{mm} \tag{3}$$

which indicates zero astigmatism at -3.1 °C, very near the -4 °C ambient temperature at which the final shim adjustments were made. The temperature coefficient of the astigmatism has been reduced from 1.38 (±0.07) mm/°C to 0.14 (±0.01) mm/°C. This order of magnitude decrease is predicted

FIGURE 3



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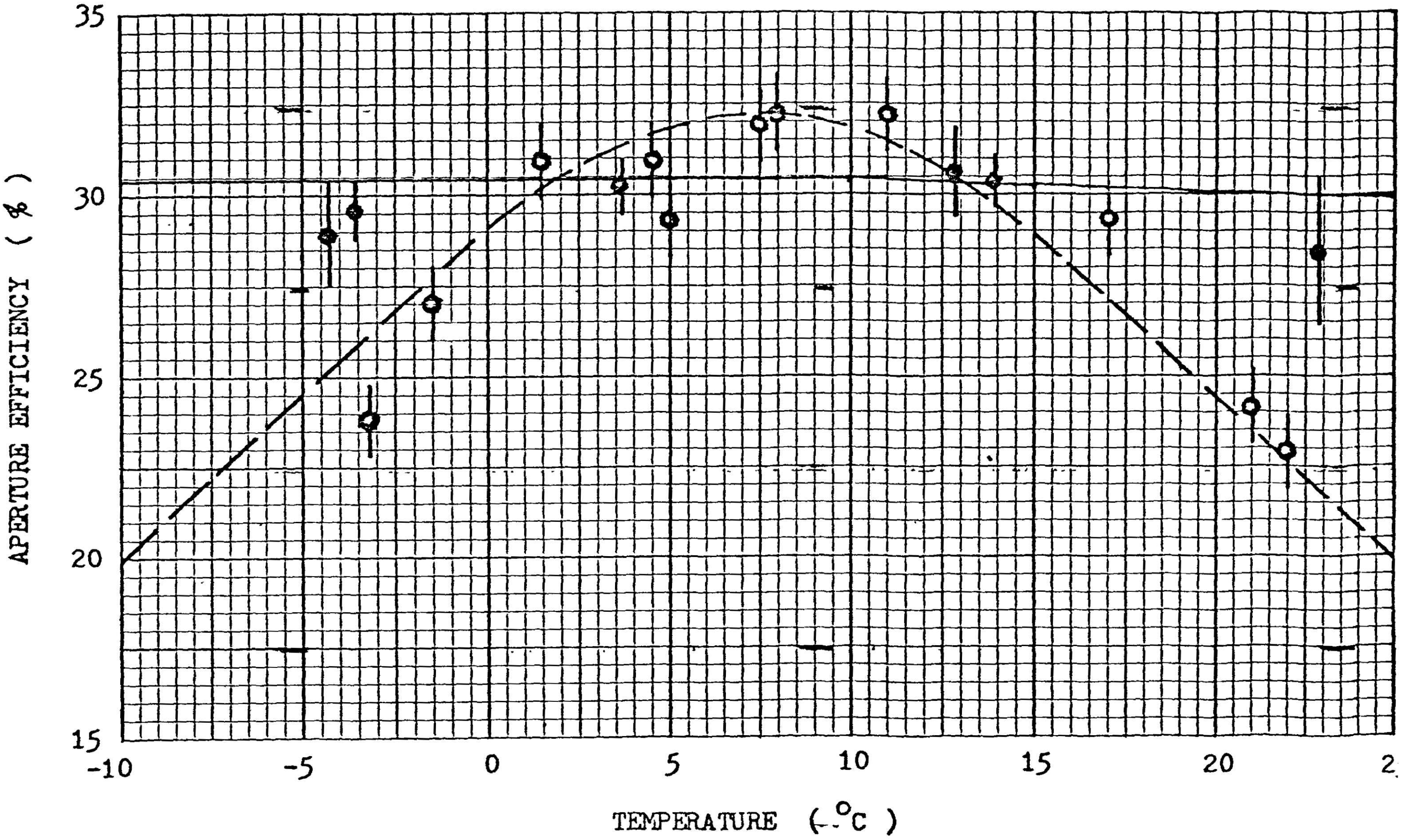
ASTIGMATISM (MM)
TEMPERATURE (°C)

by the computer model, although the absolute values of the coefficient predicted by the model are still much smaller than the observed values. Additional radiometric observations also showed that the astigmatism changed by 1.3±1.4 mm when the telescope was tilted from 26° elevation angle to 70°. This translates into a negligible change in telescope gain and indicates that gravitational effects are small.

Figure 4 is a plot of measured aperture efficiency versus temperature. Again, the filled circles are the new data for the modified telescope and the open circles are the data for the original structure. The solid line is the predicted behavior of the new structure based on the thermal astigmatism given by Equation 3 and the gain formula of Equation 2 (assuming a maximum aperture efficiency of 30.4%). Direct measurements of aperture efficiency are seen to be consistent with these calculations and indicate a maximum gain variation of less than 7% over the entire range of ambient temperature. The peak gain of the modified telescope is about 5% lower than before, but this was expected due to the increased dead load deformations. This slight loss in peak efficiency is more than offset by the much improved gain in cold and hot weather. In addition, the improved diurnal gain stability will allow more accurate continum observations than previously possible.

Table I is a summary of observations and computer model predictions for both the original and the modified structures. The model accurately predicts the change in best focus with temperature and with elevation angle for both structures, and it also predicts the large improvement in thermal astigmatism.

FIGURE 4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APERTURE EFFICIENCY (%)
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-5
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TEMPERATURE (°C)

TABLE I

FOCUS DATA SUMMARY

Quantity	Original Structure		Modified Structure	
	Model Prediction	Measured Value	Model Prediction	Measured Value
Focus constant (mm) $(T=7.5^\circ C,\ EL=90^\circ)$		28.0 ± 0.5	-	30.8 ± 0.5
$\frac{\partial(\text{Focus})}{\partial(T)}$ $(\text{mm}/^\circ C)$	0.33	0.23 ± 0.10	0.28	0.27 ± 0.10
$\frac{\partial(\text{Focus})}{\partial(T_{rim} - T_{hub})}$ $(\text{mm}/^\circ C)$		3.9 ± 0.5		3.6 ± 0.5
$\frac{\partial(\alpha)}{\partial(T)}$ $(\text{mm}/^\circ C)$	0.21	1.38 ± 0.07	-0.02	0.14 ± 0.01
$\frac{\partial(\text{Focus})}{\partial(\text{Sin EL})}$ (mm)	1.7	1.6 ± 1.0	2.1	2.0 ± 1.0
$T(\alpha=0)$ $(^\circ C)$		7.5 ± 0.6	-	-3.1 ± 0.3

VI. CONCLUSIONS AND RECOMMENDATIONS

The thermal astigmatism of the 36-foot telescope was due to differential thermal expansion of the steel backup structure and the aluminum reflector. A computer model of the telescope has been written which correctly predicts the gravitational behavior and many of the observed thermal characteristics of the telescope. This model was used to design passive structural modifications which were implemented. The thermal behavior of the modified structure has been observed over a wide temperature range. A substantial improvement in the average value of telescope gain has been achieved. In addition, the variation of gain with temperature has been significantly reduced, allowing more repeatable (and thus more accurate) astronomical observations to be made. Another benefit of the structural modifications is a reduction in the lower elevation limit of the telescope from 15.2° to 12.5°, allowing more time for observations of extremely low-declination sources such as Centaurus A. The slight reduction in peak gain can probably be recovered by lifting the feed legs and readjusting the backup structure and feed leg shims. Hopefully this will be accomplished during the summer extended maintenance period.

The 36-foot telescope is a gravitationally stiff and thermally stable platform which is capable of supporting a more accurate mirror. Presently the telescope performance at short wavelengths is limited by original machining errors and by dents from the feed leg accident. These are repairable by either filling in the depressions in the primary mirror with aluminum tape or by machining a phase-error correcting subreflector. However, the residual surface errors are not now well known, and the most difficult part of any project to improve the surface accuracy will be to map these errors in great detail. Some possible measuring methods are the stepping bar and electronic level, a parabolic template, or microwave holography. I suggest that an effort be made to accurately measure the errors in the 36-foot reflector, since correcting them is straightforward and inexpensive and will result in significantly improved telescope gain at high frequencies.

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