Thermo-optical analysis of two long-focal-length aerial reconnaissance lenses

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Abstract. A 36-inch f/5.0 lens and a 24-inch f/3.5 lens used for aerial reconnaissance missions are described. During design, these lenses were analyzed over their full operating temperature range of 20 to 60 C. Their performance at ambient conditions and at the maximum operating temperature is reported. The results indicate that, at steady state, the performance of each lens is affected only modestly over the operating temperature range when the image is held in focus by a thermal compensating lens mount.

Keywords: optomechanical design; reconnaissance lenses; optical design; thermal effects; adverse environments; mount design.

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CONTENTS

1. INTRODUCTION

The Perkin-Elmer Corporation designed and built two long-focal-length aerial reconnaissance lenses: a 24-inch f/3.5 lens and a 36-inch f/5.0 lens. Both lenses were designed to be compatible with the KA-50 series camera which has a 4.5-inch-square film format. Both were designed to operate in a controlled environment of 20 C to 60 C.

2. 24-INCH f/3.5 LENS PERFORMANCE ANALYSIS

The 24-inch f/3.5 optical schematic is shown in Fig. 1. The design consists of eight elements with the fourth and fifth elements cemented. Although the design cannot be identified as any particular form, it may be considered as a derivative of a double Gauss, with the third and sixth elements constituting the negative core of the double Gauss and the first, second, seventh, and eighth elements, the surrounding positive elements. The fourth and fifth cemented elements, located inside the Gauss core near the stop, provide additional degrees of freedom for aberration correction. All of the negative elements are of the short flint-type glass, and the fifth element is a long crown type. These glasses were used to reduce the secondary spectrum. The optical performance requirements are listed in Table I.

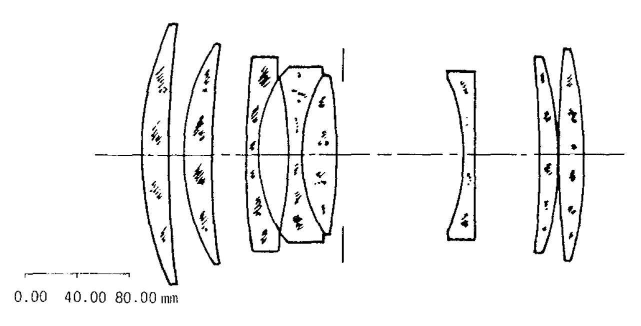

Fig. 1 Schematic diagram of a 24-inch f/3.5 lens.

The performance of the 24-inch f/3.5 design was evaluated first at the ambient condition of 20 C. Then the radii, axial thicknesses, air spaces, and indices of refraction were calculated at 60 C, and the system was reevaluated. The transverse aberration curves for 20 C and 60 C are shown in Figs. 2 and 3. The polychromatic optical transfer function (OTF) is shown in Figs. 4 and 5. The modulation detectability M_d is plotted for Panatomic-X film so that resolution on that film can be determined.

A comparison of the aberration curves in Figs. 2 and 3 shows that on-axis, the balance of focus shift, third and fifth order spherical aberration, was slightly upset at 60 C. In the field there was a slight change in the coma, and the lateral color was slightly increased.

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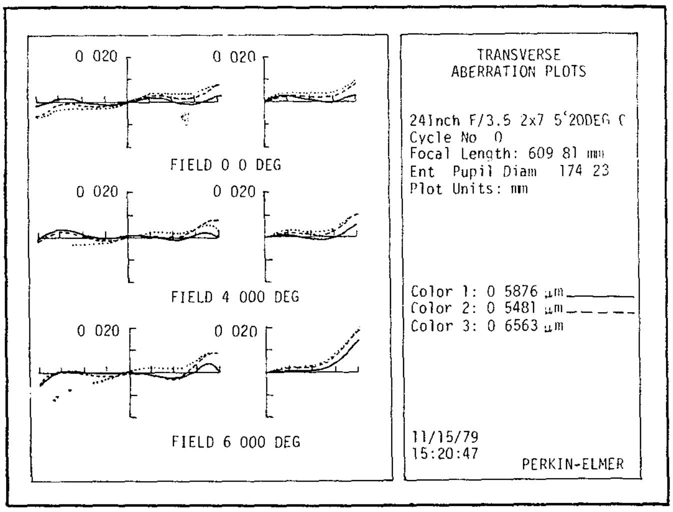
TABLE I Optical Performance Requirements of the 24-inch f/3 5 Lens

Focal Length	24 inches ±1%
f-number	f/3 5, variable to f/11
Resolution	110 lines/mm high contrast, on Panatomic-X (type-136) film with minus blue filter (Wratten No 12 equivalent)
Axial Transmission	82% minimum
Relative Illumination	77% minimum at 6 degrees off axis
Veiling Glare	2% maximum
Environment	The resolution shall not be degraded by more than 10% at any steady-state temperature in the range of 20 C to 60 C



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TRANSVERSE
ABERRATION PLOTS

24Inch F/3.5 2x7 5'20DEG C
Cycle No  0
Focal Length: 609 81 mm
Ent  Pupil Diam  174 23
Plot Units: mm

Color 1: 0 5876 µm________
Color 2: 0 5481 µm_ _ _ _ _
Color 3: 0 6563 µm

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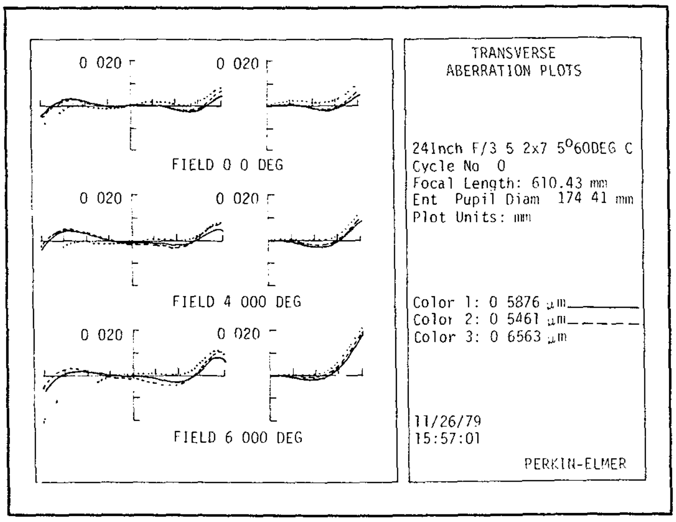
Fig 2. Transverse aberration curves for 24-inch f/3 5 lens at 20 C



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TRANSVERSE
ABERRATION PLOTS

24Inch F/3 5 2x7 5°60DEG C
Cycle No  0
Focal Length: 610.43 mm
Ent  Pupil Diam  174 41 mm
Plot Units: mm

Color 1: 0 5876 µm________
Color 2: 0 5461 µm_ _ _ _ _
Color 3: 0 6563 µm

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Fig 3 Transverse aberration curves for 24-inch f/3 5 lens at 60 C

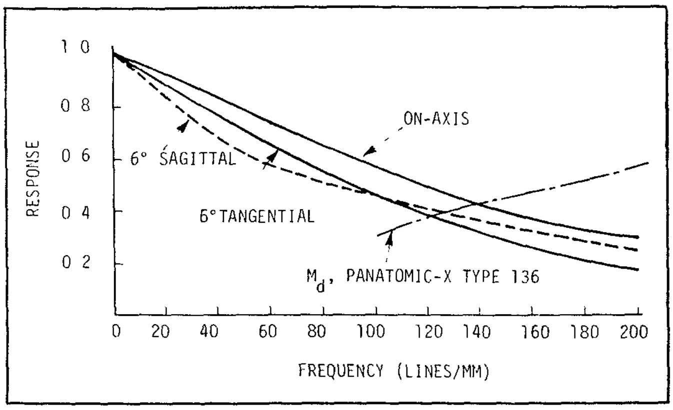

Fig. 4 Polychromatic optical transfer function for 24-inch f/3 5 lens at 20 C

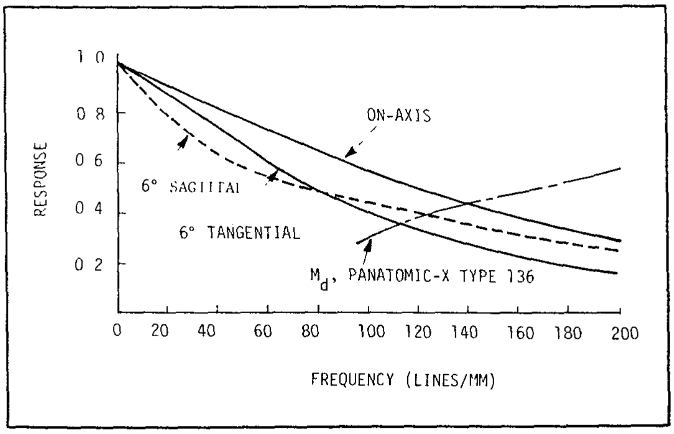

Fig 5 Polychromatic optical transfer function for 24-inch f/3 5 lens at 60 C

TABLE II. Predicted Resolution on Panatomic-X (Type 136) Film for the 24-inch f/3 5 Lens with Minus Blue Filter

	Resolution (lines/mm)		
Field Angle	At 20 C	At 60 C	% Change
On-axis	140	140	0
6 deg sagittal	126	123	−2
6 deg tangential	122	113	−9

A comparison of the polychromatic OTF in Figs 4 and 5 shows a slight reduction in predicted response at 60 C The intersection of the M_d curve for the film and the response for the lens gives the predicted resolution

The predicted resolutions for 20 C and 60 C are shown in Table II, and the predicted changes in resolution are also given The on-axis resolution remains unchanged The off-axis sagittal resolution was slightly affected with a 2 percent reduction The tangential resolution dropped by 9 percent This change is attributed primarily to the change in lateral color The analysis indicates that the maximum allowed degradation of 10 percent has been met

The effect of the temperature change on the other performance requirements listed in Table I are negligible Performance evaluation at intermediate temperatures was not necessary since, over the relatively narrow temperature range of 20 C to 60 C, the performance is linear

3. 36-INCH f/5.0 LENS PERFORMANCE ANALYSIS

The 36-inch f/5 0 optical schematic is shown in Fig 6 The design consists of seven elements with the first and second, and the sixth and seventh elements cemented This form has been referred to as a plasmat form The form may be considered a triplet surrounded by two thick shells All of the negative elements are made of short flint-type glass in order to reduce the secondary color The optical performance requirements are listed in Table III

The performance of the 36-inch lens design was evaluated at the ambient condition of 20 C Then the radii, axial thicknesses, air spaces, and indices of refraction were calculated at 60 C and the

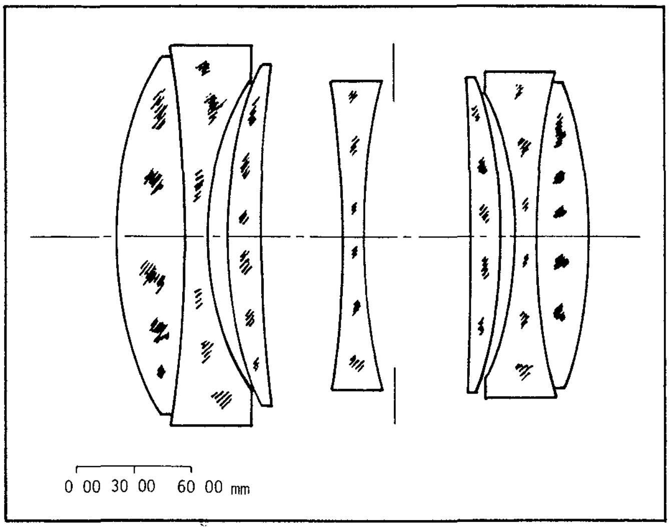

Fig 6 Schematic diagram of a 36-inch f/5 0 lens

TABLE III Optical Performance Requirements of the 36-inch f/5 0 Lens

Focal Length	36 inches ±1%
f-number	f/5 0, variable to f/11
Resolution	100 lines/mm high contrast, on Panatomic-X Type-136 film with minus blue filter (Wratten No 12 equivalent)
Axial Transmission	70% minimum
Relative Illumination	70% minimum at 4 5 degrees off axis
Veiling Glare	2% maximum
Environment	The resolution shall not be degraded by more than 10% at any steady-state temperature in the range of 20 C to 60 C

design reevaluated The transverse aberration curves for 20 C and 60 C are shown in Figs 7 and 8 The polychromatic OTF is shown in Figs 9 and 10

A comparison of the aberration curves in Figs 7 and 8 shows that on-axis, the balance of focus shift, third and fifth order, was slightly upset at 60 C The effect on field aberrations was negligible, however, the change in spherical aberration was additive in the sagittal field, where the spherical aberration was most strongly felt

A comparison of the polychromatic OTF in Figs 9 and 10 shows a slight reduction in predicted response at 60 C The predicted resolutions for both temperatures are shown in Table IV The on-axis resolution dropped by 2 percent The off-axis sagittal resolution dropped by 10 percent This is attributed primarily to the cumulative effect of the change in spherical aberration The tangential resolution dropped by 2 percent The analysis shows that the required maximum degradation of 10 percent has been met

The effect of the temperature change on the other performance requirements listed in Table III is negligible Performance evaluation at intermediate temperatures was not necessary since, over the relatively narrow temperature range of 20 C to 60 C, the performance is linear

4. GENERAL CONSIDERATION OF THE THERMAL ANALYSIS

All of the above results were based on two assumptions that, at 60 C, steady-state conditions have been reached and that the results are reported at the plane of best focus

Empirical tests run by Geary[1] on the 24-inch f/3 5 and the 36-inch f/5 0 lenses, as well as on other long-focal-length lenses, confirm the fact that, during the transient period, performance is reduced and that, in order to achieve the full predicted performance over the temperature range, sufficient time must be provided in which to achieve thermal equilibrium Geary states that the camera bay (or pod) must provide a long-term stable thermal environment for the objective regardless of outside ambient temperatures and their rates of change and that the camera bay should be brought to system operational temperature several hours before the pilot begins his

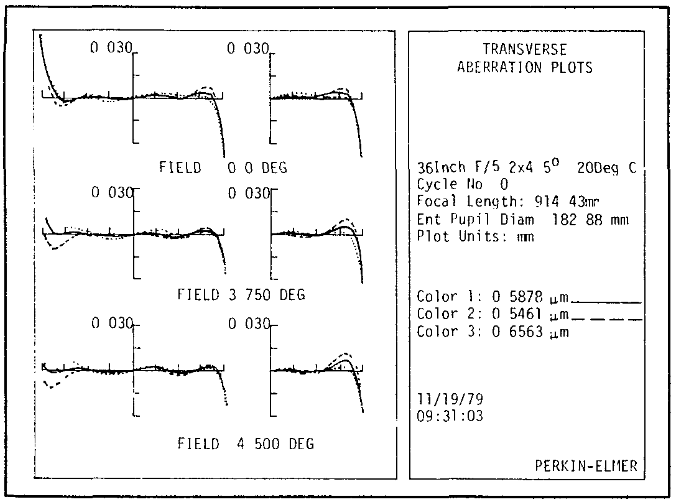

Fig 7 Transverse aberration curves for 36-inch f/5.0 lens at 20 C

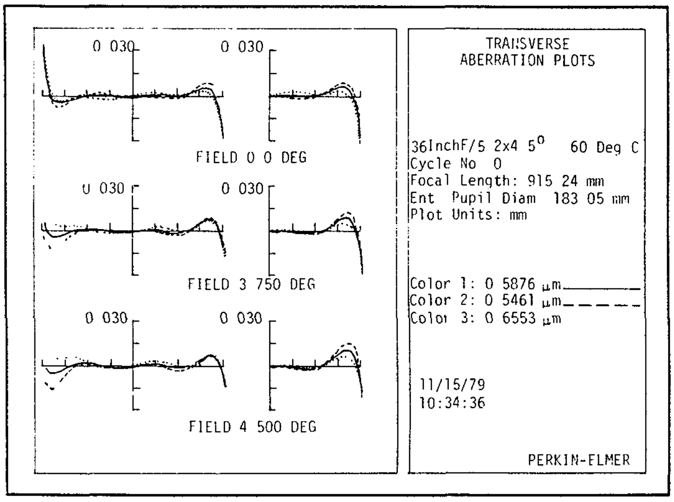

Fig 8 Transverse aberration curves for 36-inch f/5 0 lens at 60 C

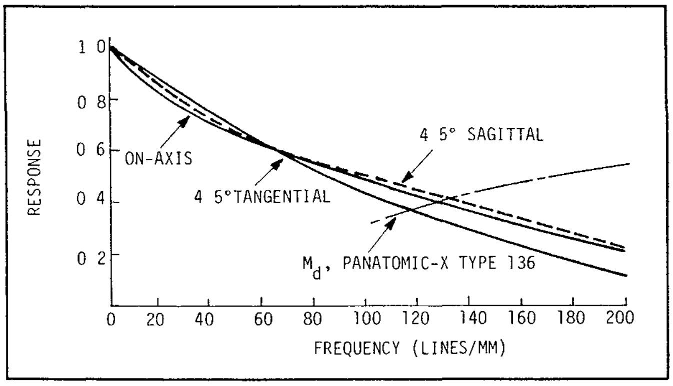

Fig 9 Polychromatic optical transfer function for 36-inch f/5 0 lens at 20 C

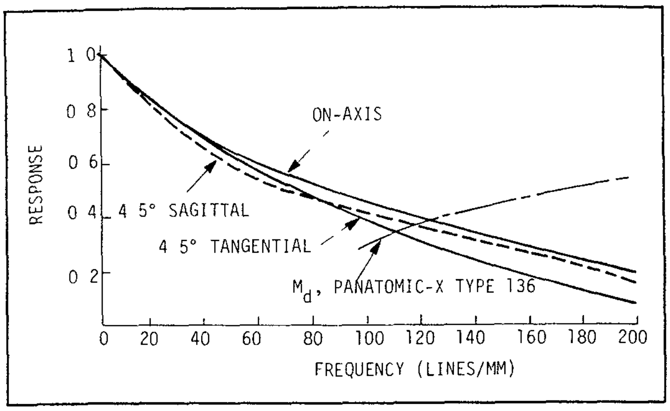

Fig 10 Polychromatic optical transfer function for 36-inch f/5 0 lens at 60 C

TABLE IV Predicted Resolution on Panatomic-X (Type 136) Film for the 36-inch f/5 0 Lens with Minus Blue Filter

	Resolution (lines/mm)		
Field Angle	At 20 C	At 60 C	% Change
On-axis	127	124	−2
4 5 deg sagittal	132	119	−10
4 5 deg tangential	117	115	−2

mission This will ensure that the lens has had sufficient time to recover from the transient state

5. THERMAL COMPENSATION OF THE CHANGE IN BACK FOCAL LENGTH (BFL)

The thermal analysis of the 24-inch f/3 5 lens indicated that its back focal length (BFL) increased from 365 646 mm at 20 C to 365 949 mm at 60 C for a change of 0 303 mm The same analysis of the 36-inch f/5 0 lens indicated that its BFL increased from 757 255 mm at 20 C to 758 000 mm at 60 C for a change of 0 745 mm Clearly, if compensation were not provided for these changes in BFL, performance would be adversely affected If the bay or pod is temperature controlled within a few degrees, all that is required is to focus the lens at the temperature at which it will be used If the lens will operate over the full temperature range of 20 C to 60 C, a suitable thermal-compensating lens mount must be provided This requirement is typical of sophisticated high performance optical systems

Preliminary designs of bimetallic lens mounts for both lenses are shown in Figs 11 and 12 Thermal compensation can be achieved by suitably apportioning between these metals the total path length from the lens flange to the film plane (FFL) In each design, the two metals used are aluminum and stainless steel The aluminum (al) is type 6061, with a coefficient of thermal expansion, α, of 236×10^{-7} mm/mm/°C The stainless steel (ss) is type 416SE, with an α of 99×10^{-7} mm/mm/°C Also, in each case, the cell c is type 2024 aluminum with an α of 232×10^{-7} mm/mm/°C The calculations to determine the appropriate thicknesses of the two metals to achieve BFL thermal compensation for each design are given in the following paragraphs

6. BIMETALLIC THERMAL-COMPENSATING LENS MOUNT FOR THE 24-INCH f/3.5 LENS

The schematic diagram for the 24-inch f/3 5 lens mount is shown in Fig 11 Thermal compensation for this design is calculated as follows:

$$\Delta \mathrm{BFL} = \mathrm{BFL}' - \mathrm{BFL}$$

$$= \left[\alpha_{al} t_{al} + \alpha_{ss} t_{ss} - \alpha_c t_c - \alpha_l t_l\right] \Delta T , \quad (1)$$

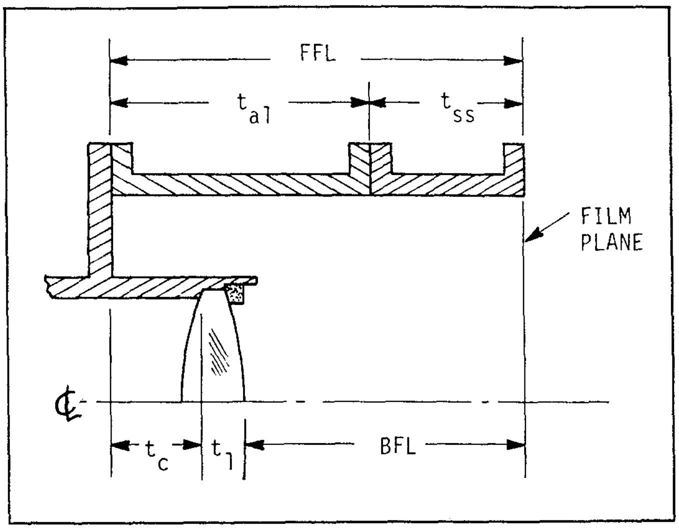

Fig 11 Schematic diagram of thermal-compensating mount for the 24-inch f/3 5 lens

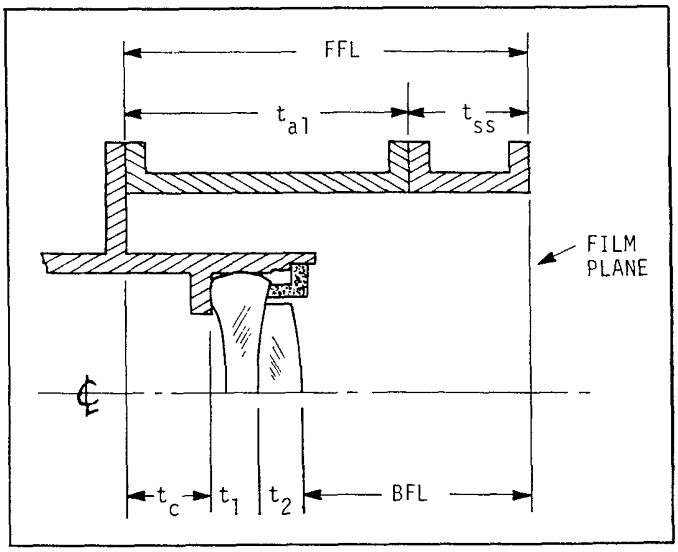

Fig 12 Schematic diagram of thermal-compensating mount for the 36-inch f/5 0 lens

where

BFL = back focal length at 20 C = 365 646 mm
BFL' = back focal length at 60 C = 365 949 mm
$\Delta\mathrm{BFL}$ = 0 303 mm
α_l = 63×10 mm/mm/°C
t_l = 15 252 mm
t_c = 154 102 mm
$\Delta T = 60° - 20° = 40°$

Substituting these values into Eq (1) gives

$$236 t_{al} + 99 t_{ss} = 112{,}462\ 54 \text{ mm} \quad (2)$$

The combined thicknesses of the two metals equal the flange focal length (FFL),

$$t_{al} + t_{ss} = \mathrm{FFL}, \quad (3)$$

where FFL = 535 0 mm

Solving Eqs (2) and (3) for t_{al} and t_{ss} yields

$$t_{ss} = 100\ 711 \text{ mm}$$
$$t_{al} = 434\ 289 \text{ mm}$$

7. BIMETALLIC THERMAL-COMPENSATING LENS MOUNT FOR THE 36-INCH f/5.0 LENS

The schematic diagram for the 36-inch f/5 0 lens mount is shown in Fig 12 Thermal compensation for this design is calculated as follows:

$$\begin{aligned}\Delta BFL &= BFL' - BFL \\ &= [\alpha_{al} t_{al} + \alpha_{ss} t_{ss} - \alpha_c t_c - \alpha_1 t_1 - \alpha_2 t_2]\,\Delta T\,, \qquad (4)\end{aligned}$$

where

$BFL = 757\ 255$ mm

$BFL' = 758\ 000$ mm

$\Delta BFL = 0\ 745$ mm

$\alpha_1 = 60 \times 10$ mm/mm/°C

$\alpha_2 = 62 \times 10$ mm/mm/°C

$t_1 = 25\ 800$ mm

$t_2 = 27\ 200$ mm

$t_c = 21\ 595$ mm

$\Delta T = 40°$

Substituting these values into Eq (4) gives

$$236 t_{al} + 99 t_{ss} = 194{,}494\ 44 \text{ mm} \qquad (5)$$

The combined thicknesses of the two metals equal the flange focal length (FFL) [Eq (3)] In this design, FFL is 831 850 mm Solving Eqs (3) and (5) for t_{al} and t_{ss} yields

$$t_{ss} = 13\ 300 \text{ mm}$$
$$t_{al} = 818\ 550 \text{ mm}$$

8. CONCLUSIONS

The thermo-optical characteristics of a 24-inch f/3 5 lens and a 36-inch f/5 0 lens were analyzed Both lenses exhibited less than a 10 percent reduction in resolution at steady-state temperature and at best focus over a temperature range of 20 C to 60 C The preliminary designs of thermal compensating mounts for both lenses described here adequately compensate for the change in back focus as a function of temperature over this range

9. ACKNOWLEDGMENTS

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10. REFERENCES

1 J M Geary, Proc SPIE 193, 108(1979)