MEMORANDUM
To: Dan Fabricant
From: Warren Brown
Date: 23 May 2002
Subject: Binospec Thermal Analysis IV: Results for the Optics

1. INTRODUCTION

This is the fourth of a series of memos concluding the Binospec thermal analysis. This memo focuses on the thermal response of the collimator and camera optics to external environment temperature changes and internal heat sources. I briefly review the physical data on the optics and outline the assumptions made in our models. I then discuss the thermal time constants and temperature gradients calculated from our models. I finish by considering the thermal effects on the optics of operating the stepper motors and changing slit masks.

2. DATA

2.1. Optical & Mechanical Information

In brief, the Binospec collimator and camera are refractive designs made of 3 lens groups each. Figure 1 shows the optical layout. The material properties are listed in Appendix A; glass information was obtained from Ohara, and the CaF_2 and NaCl data was obtained from Optovac.

The lenses are bonded to aluminum bezels by RTV pads. Figure 2 shows the collimator mount; the camera mount is similar in construction, minus the fold mirror.

2.2. Models and Assumptions

The following results make use of the low-resolution Binospec model. The model treats the spectrograph as a number of masses connected by a network of conductive, convective, and radiative paths, and is described in detail in the "Description of the Thermal Model" memo. As a reminder, Figure 3 illustrates the node map for the collimator and camera.

The baseline Binospec model makes the following important assumptions: 1) 3 inch thick urethane foam surrounding Binospec, 2) a 28 inch diameter entrance window at the top, 3) an exterior convection coefficient of $h = 18$ W m^{-2} K^{-1}, 4) an interior convection coefficient $h = 2$ W m^{-2} K^{-1} (for still air in an enclosed space), and 5) no active motors. Decreasing the foam insulation thickness to 1 inch or removing the entrance window increases temperature gradients up to a factor of 2 over the baseline model. Varying convection coefficients and motor usage changes the temperature gradients by less than $\pm 20\%$. The "Baseline Model Results" memo discusses the model variations in more detail.

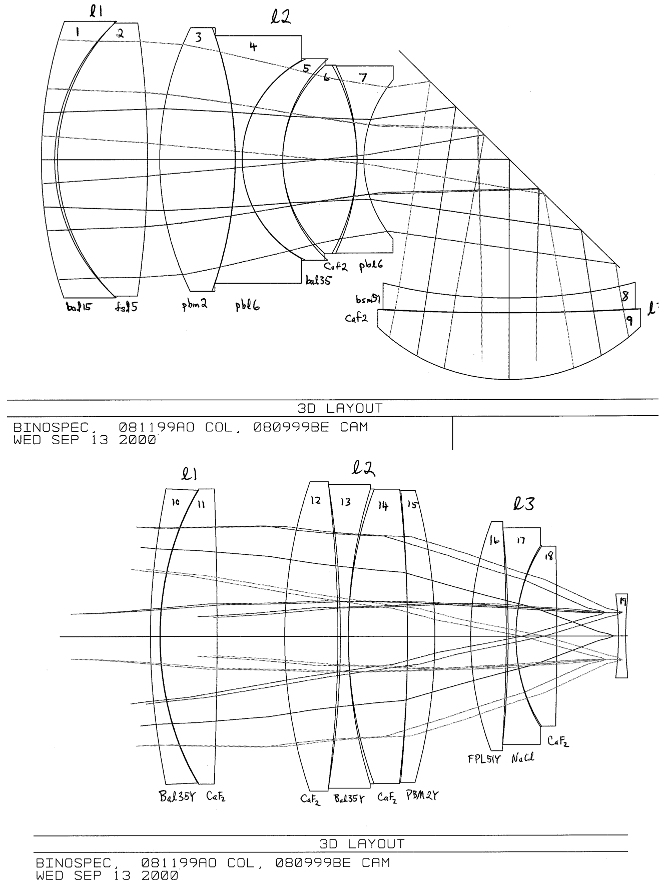

Fig. 1.— Optical layouts of the Binospec collimator (top) and camera (bottom).

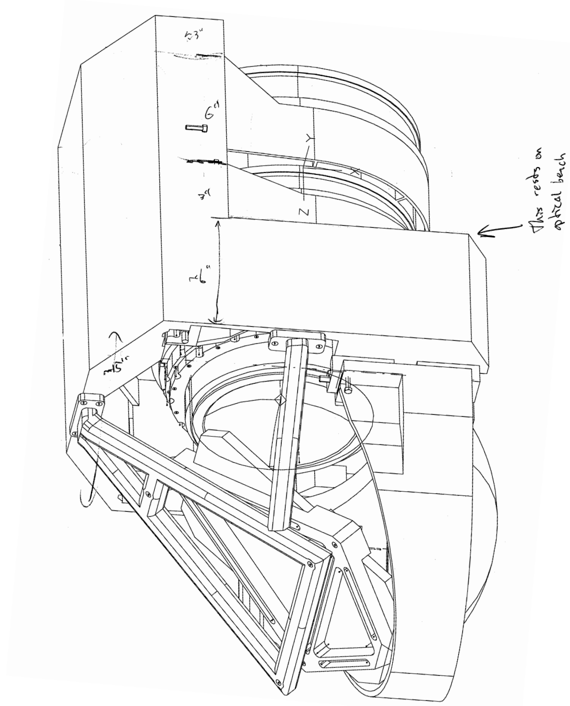

Fig. 2.— Collimator structure.

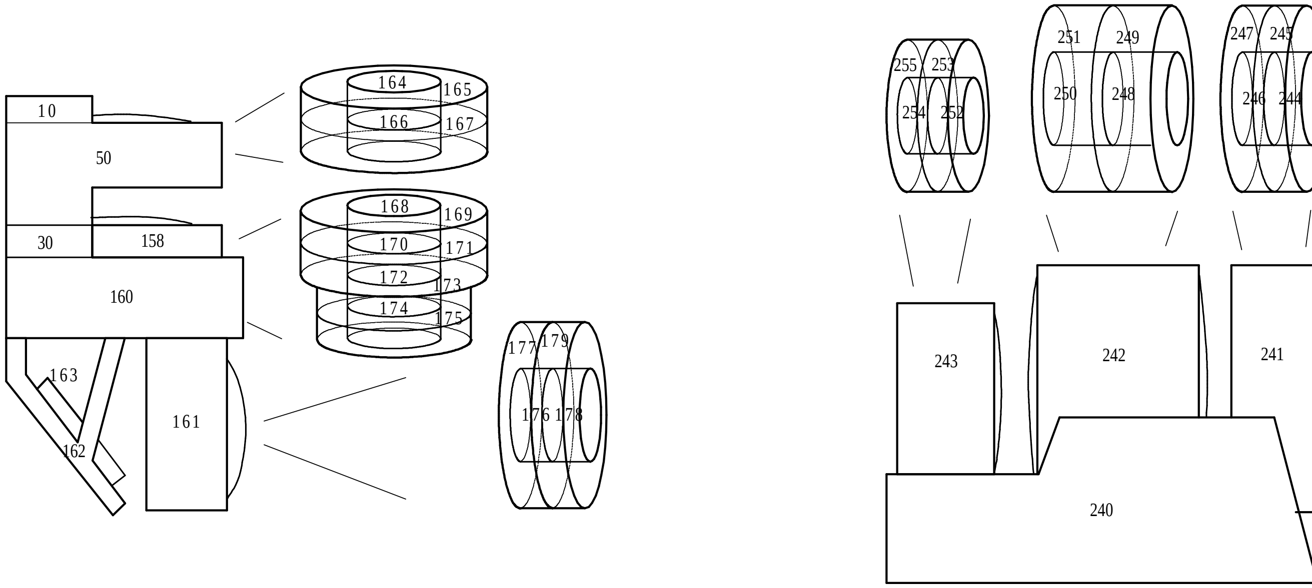

Fig. 3.— Node map of the collimator and camera in the Binospec model. The lens groups are modeled with two or more axial and radial slices; the bezels are modeled as single nodes.

3. RESULTS

I begin by looking at the thermal capacitances of the optics and thermal diffusivities of the materials. These quantities establish a picture for the thermal time constants and temperature gradients in the optics. Two objects in the same temperature environment (i.e. a telescope dome) but with different thermal time constants will have a temperature gradient between them. I also estimate the effects of operating motors and changing slit masks.

3.1. Thermal Capacitances

Thermal time constants are proportional to the mass m and specific heat C of an object; the greater the "thermal capacitance" mC of an object, the longer its response to the environment. Table 1 lists the thermal capacitances of the lens groups and the bezels. The thermal capacitances are the (Zemax) lens masses multiplied by the (Ohara or Optovac) specific heats, summed for a lens group. For reference, Figure 4 shows the location of the lens groups on the optical bench.

Lens groups 2 of the collimator and camera have twice the thermal capacitance of their companion lens groups (Table 1). The different thermal capacitances will naturally lead to different time constants, and thus temperatures differences, between the lens groups. This is further excaberated by both lens groups 2 having half as much surface area per unit mass than the other lens groups, and being convectively and radiatively shielded by the collimator shroud or camera barrel.

TABLE 1
Thermal Capacitances

Object	lens grp mC (J/K)	bezel mC (J/K)
Collimator		
lens group 1	15700	5900
lens group 2	26100	16200
lens group 3	12400	6550
Camera		
lens group 1	20800	3200
lens group 2	47000	7550
lens group 3	13000	4100

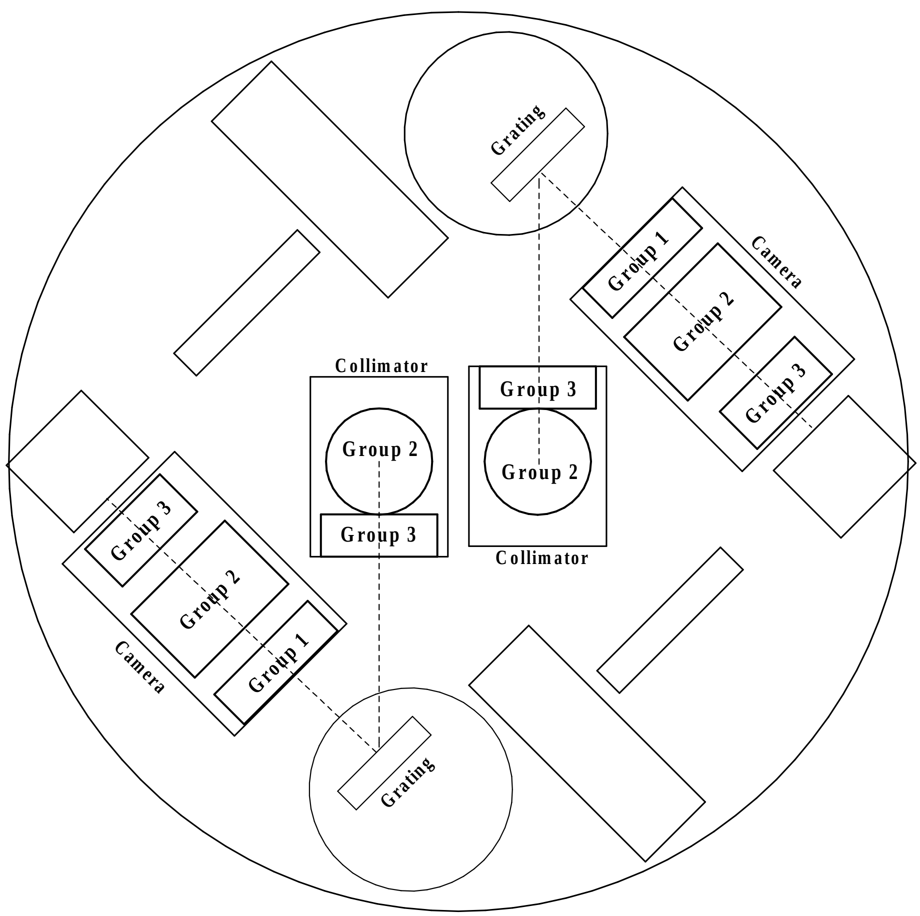

Fig. 4.— Location of the collimator and camera lens groups bezels on the bottom of Binospec optical bench.

3.2. Thermal Diffusivity

Thermal diffusivity is another convenient way to compare the thermal time constants of materials listed in Appendix A. The conductive thermal time constant is inversely proportional to the thermal diffusivity $\alpha = k/\rho C$. A kilogram of aluminum ($\alpha \simeq 50 \times 10^{-6}$ m^2 s^{-1}) will have a 100× shorter conductive time constant than a similarly shaped kilogram of Ohara I-line glass ($\alpha \simeq 0.5 \times 10^{-6}$ m^2 s^{-1}). This suggests that the mounting bezels will vary in temperature much more rapidly than the lenses, and thus create radial temperature gradients in the lens groups.

3.3. Time Constants

Table 2 presents the thermal time constants for the optics in the baseline Binospec model. The time constants here are e-folding times calculated by starting the baseline Binospec model 10°C above the environment and finding how long it takes the optics to equilibrate. The time constants are of order days because the baseline model is well insulated; the optical bench time constant is $\sim$ 36 hours. Where adjacent nodes have different time constants, such as the front, middle, and edge of collimator lens group 2, temperature gradients will arise.

TABLE 2
Time Constants

Object	node	τ (hrs)
Collimator		
lens group 1, core	164	41.3
lens group 2, core	168	51.7
lens group 2, edge	171	49.7
lens group 2, bezel	159	43.4
lens group 3, core	176	43.7
Camera		
lens group 1, core	244	49.2
lens group 2, core	248	53.7
lens group 3, core	254	42.7
lens group 3, edge	253	42.8
lens group 3, bezel	243	41.4

3.4. Temperature Gradients

Table 3 summarizes the worst case radial and axial temperature gradients in the optics for 10 days of “typical” and “extreme” MMT temperatures. The largest temperature differences are $\sim$ 0.5°C differences between the lens groups. The largest temperature gradients are $\sim$ 0.1°C center-to-edge radial gradients in the lenses. The next largest temperature gradients are $\sim$ 0.05°C axial gradients through the lens groups.

TABLE 3
Temperature Gradients

Objects	$\Delta T_{typical}$ (±°C)	$\Delta T_{extreme}$ (±°C)
Collimator lens group 2		
front - to - back	.035	.05
center - to - edge	.12	.18
between lens groups	.60	.90
Camera lens group 3		
front - to - back	.075	.11
center - to - edge	.08	.12
between lens groups	.50	.75

Figure 5 plots the lens group temperatures for the collimator and camera over time, using the "typical" MMT dome temperatures as a boundary condition for the baseline Binospec model. Note how collimator lens group 2 lags the other collimator lens groups by 6 hrs in time. The worst case temperature *differences* among the collimator and camera lens groups is shown in Figure 6. The temperature differences are shown for the baseline Binospec model, using both "typical" and "extreme" MMT dome temperatures as the environmental boundary conditions.

Figures 7 and 8 plot the worst case radial and axial temperature *gradients* in the collimator and camera lens groups. As in Figure 6, the temperature differences are shown for the baseline Binospec model, using both "typical" and "extreme" MMT dome temperatures as the boundary conditions. The maximum radial and axial temperature gradients are summarized in Table 3.

Calculations with the detailed collimator model (see the Model memo) verify the gradients presented here. Each lens group in the detailed collimator model is divided into 4 axial slices, 4 radial slices, and 8 angular slices for a total of 128 nodes per lens group. When I use the general Binospec model temperatures as boundary conditions for the detailed model, I find the radial and axial temperature gradients are the same with one main exception. The detailed model finds 50% greater axial gradients in lens group 1, but the boundary conditions between the models differ most greatly for the top of lens group 1. In addition, the angular resolution in the detailed model reveals an aysmmetry in the radial temperature gradient. The asymmetry arises because the lower halves of the collimator bezels are more massive and better shielded by the shroud than the upper halves of the bezels. The top-to-bottom temperature gradient is 25-50% of the radial temperature gradient.

I point out that the camera contains a number of CaF_2 elements which tend to reduce the radial temperature gradients (Figure 7) but increase the axial gradients (Figure 8) in the lens groups. The CaF_2 has a 10× greater conductivity than the Ohara I-line glasses.

Temperature gradients may be reduced by making the convective environment around the lens groups more similar. Keeping the air temperature above and below the optical bench the same reduces the worst collimator lens group temperature differences by 20%. Removing the camera barrel, and allowing convection on the lens group 2 surfaces, reduces the worst camera lens group temperature difference by 30%.

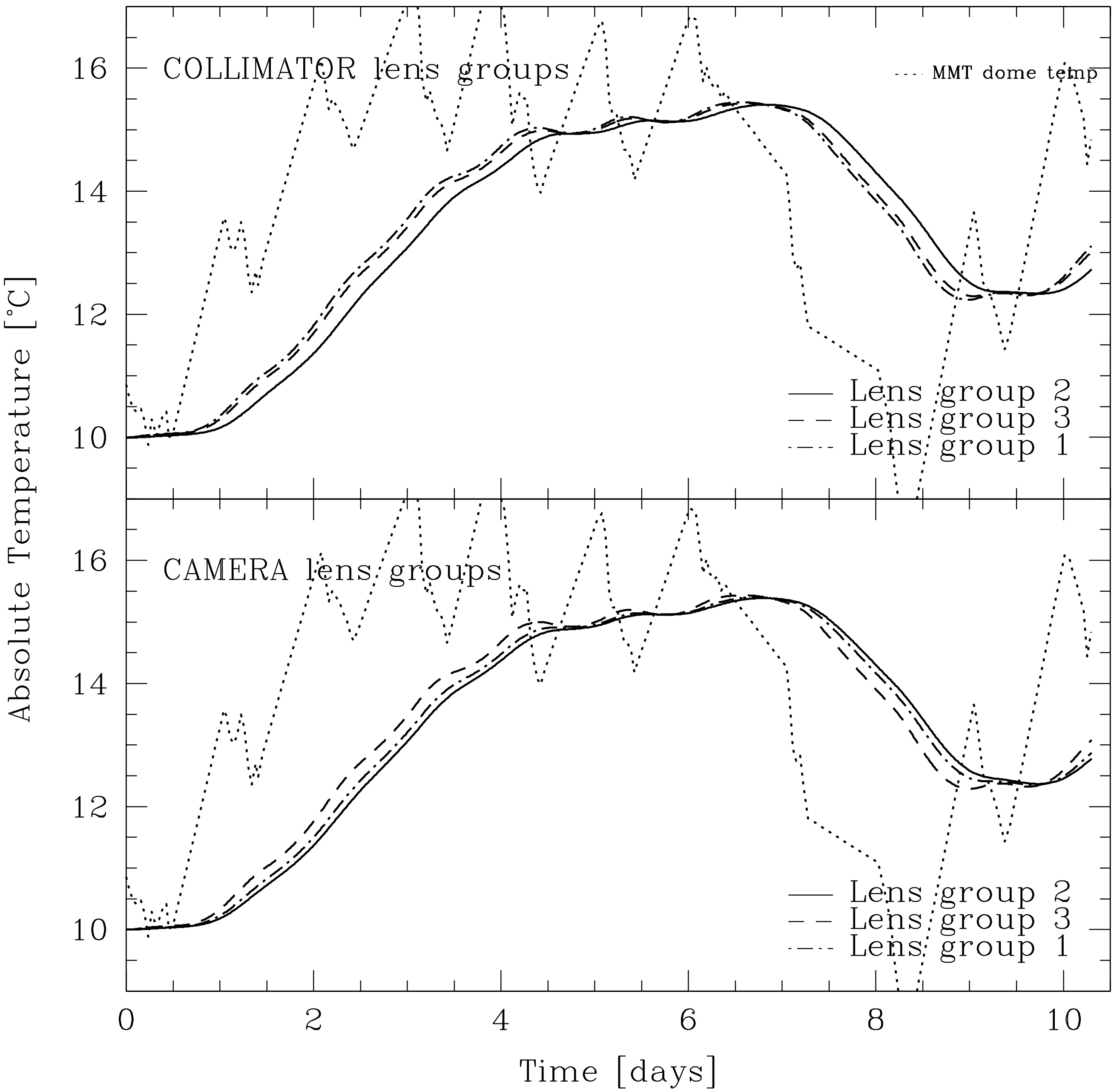

Fig. 5.— **Absolute temperatures** for the collimator (top) and camera (bottom) lens groups. The "typical" MMT dome temperatures used to drive the model are marked by the dotted line.

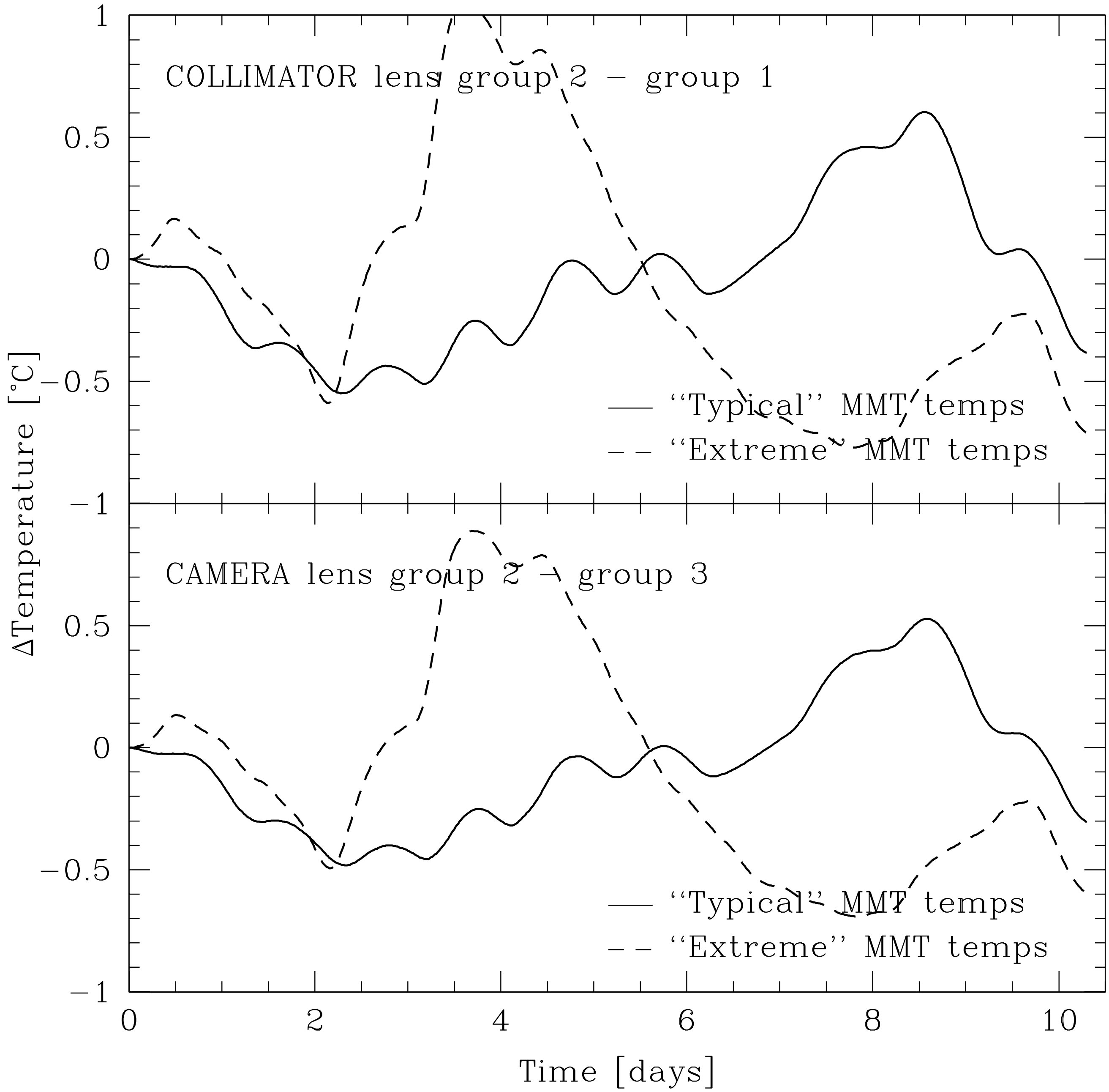

Fig. 6.— The worst-case **temperature differences** among the collimator (top) and camera (bottom) lens groups. Results are shown using both "typical" (solid line) and "extreme" (dashed line) MMT dome temperatures.

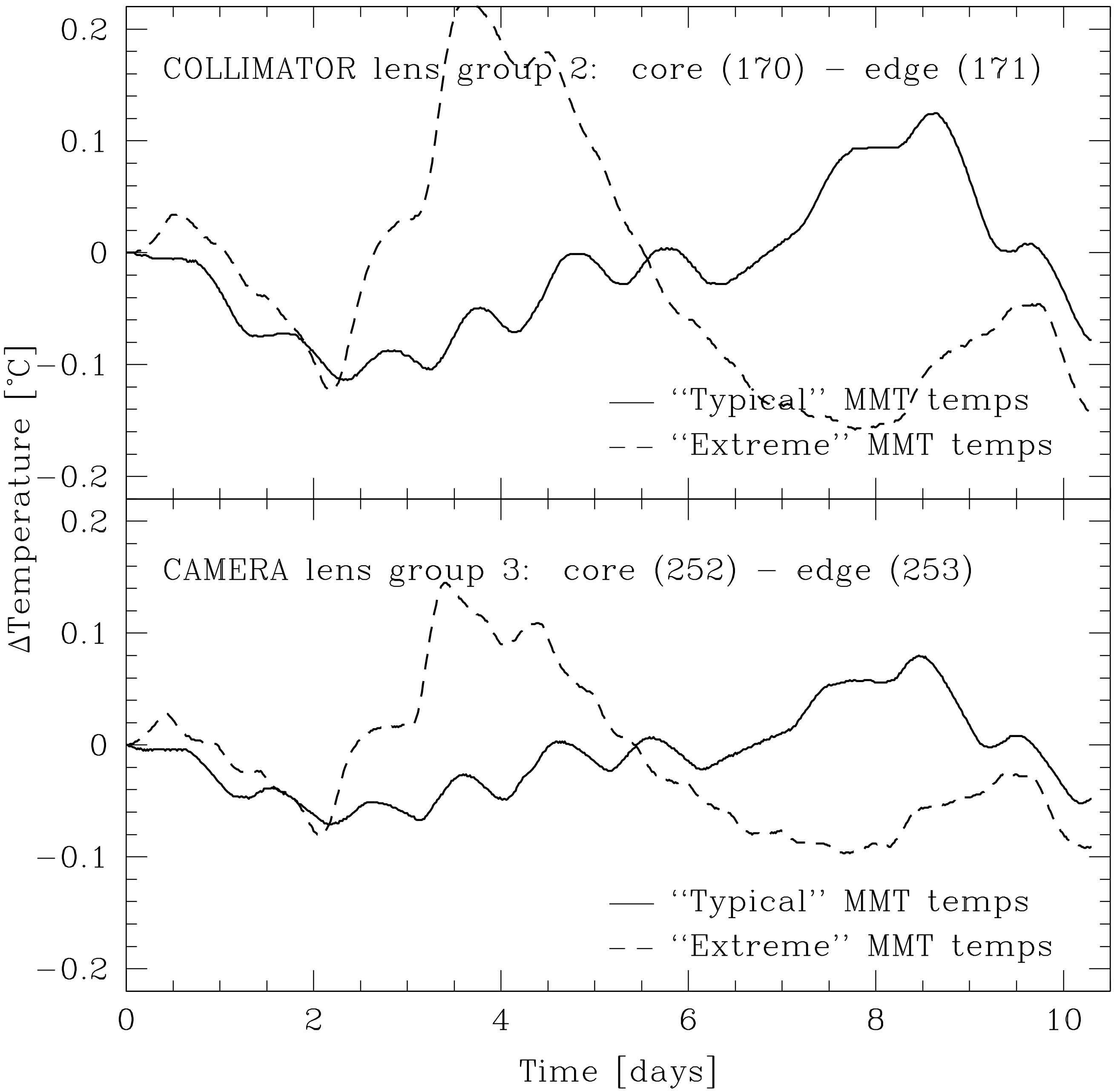

Fig. 7.— Worst case center-to-edge **radial gradients** in the collimator (top) and camera (bottom) lens groups.

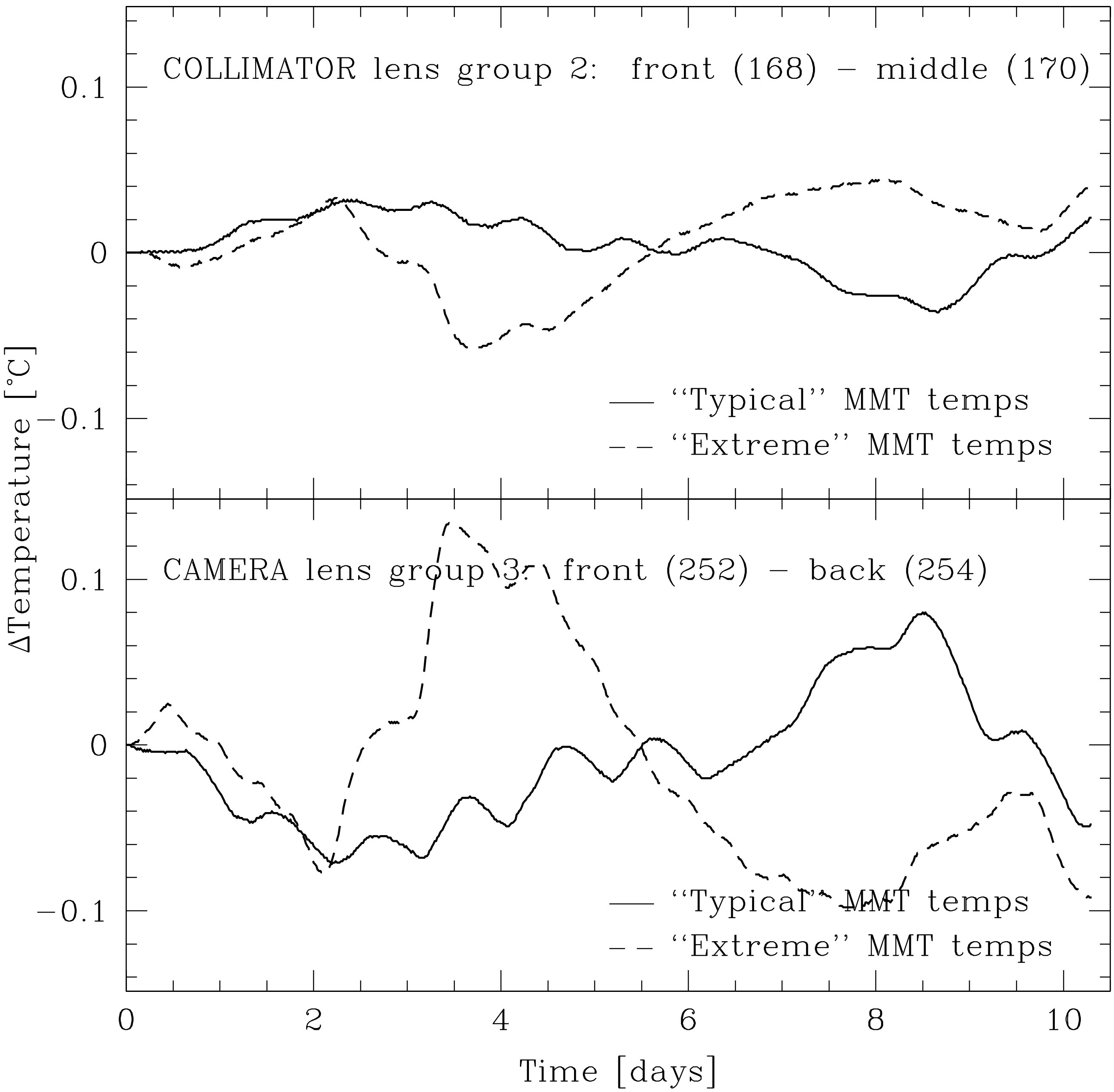

Fig. 8.— Worst case **axial gradients** in the collimator (top) and camera (bottom) lens groups.

3.5. Effect of Motors

Peak heat flow bewteen the spectrograph and the dome environment ranges is of order 30 Watts; motor heat flux averaged over time is 2.6 Watts in "imaging mode" and 0.3 Watts in "spectrograph mode." Thus temperature gradients caused by the motors are small compared to those caused by environmental changes. While there *is* an overall temperature increase in the optics of $\sim 0.05°$C after 12 hours in imaging mode, the heat propagation timescale is long enough that the optics experience a nearly uniform rise in temperature.

The worst case temperature difference induced by the motors is an extra 0.04°C increase in collimator lens group 1 due to the nearby filter changer motors. There is also an extra 0.02°C axial gradient in collimator lens group 1 (in imaging mode). All other temperature gradients — radial, axial, and lens group-to-lens group — due to the motors are less than $\pm 0.005°$C different from the baseline model.

3.6. Effect of Slit Mask Change

Changing the slit masks, filters, and gratings may potentially provide the greatest thermal shock to the spectrograph optics. The thermal capacitances of the slit masks, filters, and gratings are listed in Table 4.

TABLE 4
Thermal Capacitances

Object	mC (J/K)
10 Slit masks (0.5 kg each)	4300
12 Filters (1.2 kg each)	9400
6 Gratings (16 kg each, with holder)	79000

The slit masks will be the most frequently changed component of Binospec (potentially every day). I model a slit mask change by setting the slit masks and the air above the inner support plate a pessimistic 10°C above an otherwise uniform temperature Binospec. This input of $Q = mC\Delta T = 5 \times 10^4$ J causes additional temperature gradients throughout the spectrograph.

A slit mask change primarily affects collimator lens group 1, via heat flow through the inner support plate and fold mirror assembly. The other collimator lens groups and camera lens groups lie more protected below the optical bench. Collimator lens group 1 temperature will rise 0.06°C, resulting in an extra 0.05°C temperature difference between it and lens groups 2 and 3. The temperature difference peaks 4-5 hours after the slit mask change. There is also an extra 0.02°C axial gradient through collimator lens group 1. The axial and radial gradients in the other collimator and camera lens groups are $< 0.005°$C.

Note that changing filters is very similar to the slit mask case, except the temperature differences will be ~ 3 times greater. Changing the gratings most substantially affects the collimator and camera optics. The gratings have the longest time constant (~ 53 hrs) of any component in the spectrograph and are in close proximity to collimator lens group 3 and camera lens group 1.

Table A. Material Properties

Material	ρ (kg m^{-3})	k (W m^{-1} K^{-1})	C (J kg^{-1} K^{-1})	α (m^2 s^{-1})
Glasses				
BAL15Y	2900	1.00	700	0.49×10^{-6}
FSL5Y	2460	1.00	808	0.50×10^{-6}
PBM2Y	3610	0.814	560	0.40×10^{-6}
PBL6Y	2790	1.02	625	0.58×10^{-6}
BAL35Y	3230	0.991	600	0.51×10^{-6}
BSM51Y	3360	0.961	650	0.44×10^{-6}
FPL51Y	3640	0.780	640	0.33×10^{-6}
Average glass	3100	0.95	650	0.47×10^{-6}
Zerodur	2530	1.65	821	0.79×10^{-6}
Crystals				
CaF_2	3180	9.71	854	3.58×10^{-6}
NaCl	2165	1.15	854	0.62×10^{-6}
Connectors				
Laser liq. 5610	1072	1.47	14.7	0.93×10^{-6}
RTV 560	996	0.312	1465	0.21×10^{-6}
Metals				
Aluminum 6061	2713	164	962	62.8×10^{-6}
416 stainless	7750	24.9	460	6.98×10^{-6}
Air @ 275 K				
Air @ 2500m	0.95	0.024	1007	25×10^{-6}

Note. — ρ = density, k = conductivity, C = specific heat, $\alpha = k/(\rho C)$ = thermal diffusivity