# Thermal Considerations in Modern Spectrograph Design: the Binospec spectrograph

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## ABSTRACT

We have completed a detailed thermal analysis of Binospec, a wide-field, multi-slit spectrograph being developed for the 6.5m MMT. The goals of our analysis were to minimize temperature gradients and thermally-induced deflections and achieve a >24 hr time constant in the spectrograph optics. We consider the effects of conduction, convection, and radiation with the external environment, and model the consequences of opening a spectrograph to insert new slit masks or filters. We study when internal heat sources balance environmental effects, and the local effects of a hot motor in a spectrograph. We review the results of these thermal analyses and draw general conclusions useful to instrument builders.

**Keywords:** Spectrograph design, heat transfer

## 1. INTRODUCTION

The refractive optics used in modern astronomical instruments, including multi-object spectrographs and wide-field focal reducers, are typically designed to operate over a wide range of temperatures. However, refractive indices, lens spacings, and lens dimensions are all temperature dependent. In addition, thermal changes in the instrument structure can cause undesirable image shifts at the detector that degrade instrument calibration. It is particularly difficult to compensate for temperature *gradients* arising from temperature changes. Thus a spectrograph design should minimize thermal effects in order to achieve high image quality over a wide range of operating conditions.

We have recently completed a detailed thermal analysis of Binospec,[1] a wide-field optical spectrograph under development for the converted MMT telescope.[2] The mechanical layout of the Binospec spectrograph is shown in Figure 1. Binospec operates at the Cassegrain wide-field f/5 focus of the converted MMT.[3] Binospec uses an ambitious refractive focal reducer (collimator and camera)[4] to image two adjacent 8 arcmin by 15 arcmin fields. The original optical design was extremely sensitive to temperature changes, a problem that has been resolved using a new athermalization technique.[5] However, our concern that non-equilibrium conditions might degrade the performance of the optics motivated our thermal analysis.

Thermal analyses usually follow one of two general approaches. One approach is to find a closed form analytical solution for the heat transfer equations. Binospec is too complex for this approach. The second approach is to create a detailed thermal model of the entire instrument. We find that a complete, highly detailed model is not required to understand Binospec's thermal properties. Our approach to thermal analysis relied on a mixture of coarse and detailed models, and we believe that this approach is applicable to a variety of other instruments.

We began the Binospec analysis by calculating thermal time constants to understand the scale of temperature variations in the instrument and to determine what areas of the instrument required detailed modeling. We then generated a low-resolution finite difference thermal model of the entire spectrograph, and high-resolution models of thermally sensitive sub-assemblies. We used temperature data recorded at the MMT to set the boundary conditions for the models. We also investigated the effects of intermittent internal heat sources (motors or other

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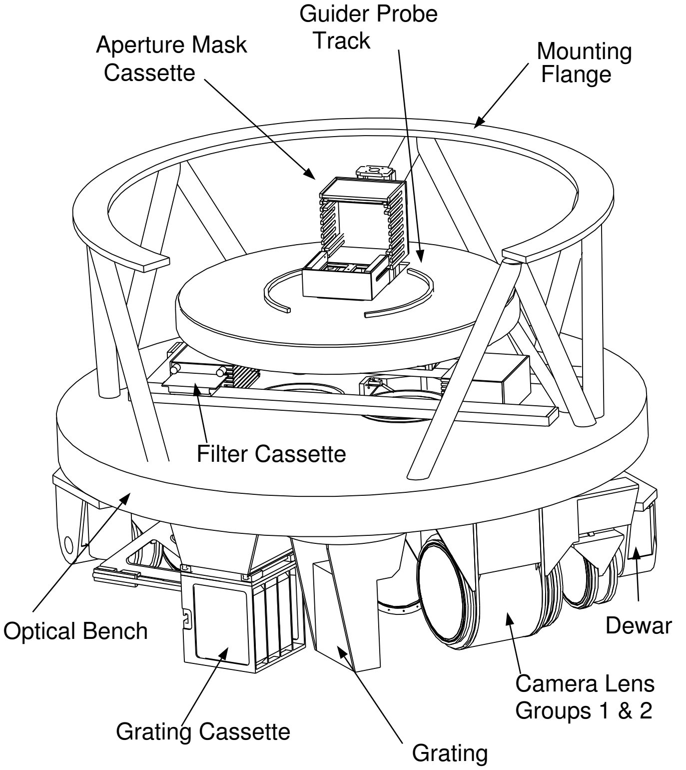

**Figure 1.** Binospec mechanical layout: top view. The optical bench is 2.14 m in diameter.

actuators) and opening the instrument to change aperture masks, filters, or gratings. The goals of the Binospec thermal analysis were to minimize temperature gradients, minimize thermally-induced deflections, and achieve a $> 24$ hr time constant in the spectrograph optics using passive techniques. We did not consider active thermal control because of practical concerns. The results of the thermal analysis are published elsewhere.[1]

The goal of this paper is to describe the thermal consequences of various design changes we investigated as part of the Binospec thermal analysis. While we are constrained to focus on Binospec as a case study, our hope is that the methods and conclusions presented here may be generalized to other instruments.

In §2 we describe thermal time constants, and their application to instrument components. In §3 and §4 we discuss the effects of the thermal environment and insulation choices. In §5 and §6 we explore thermal considerations for internal heat sources and fluid coupling layers in refractive multiplets. Finally, in §7 we discuss issues surrounding convection.

## 2. TIME CONSTANTS

Thermal time constants are a remarkably useful characterization of instrument components. An object out of thermal equilibrium with its environment will have a temperature difference that exponentially decays to zero. The rate of the exponential decay is set by the thermal time constant. The thermal time constant may be expressed as

$$\tau_{th} = R_{th} C_{th} \tag{1}$$

where $R_{th}$ is the resistance to heat transfer and $C_{th}$ is the lumped thermal capacitance. The lumped thermal capacitance is simply $C_{th} = \rho V C = mC$, where where $\rho$ is the density, $V$ is the volume, $C$ is the specific heat, and $m$ is the mass. The resistance to conduction is given by $R_{th} = L/kA_x$, where $L$ is the length of the

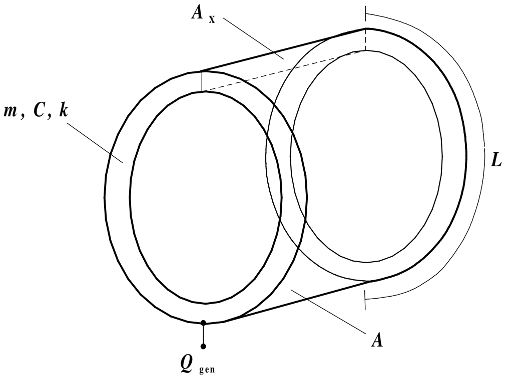

**Figure 2.** An idealized lens barrel.

conduction path, $k$ is the conductivity, and $A_x$ is the cross-sectional area. Thus the time constant for conduction is

$$\tau_{cond} = \rho C L^2/k = mCL/kA_x \tag{2}$$

Similar equations hold for time constants due to convection and radiation.[1] Conduction, convection, and radiation are all important modes of heat transfer in an instrument.

Large time constant differences between adjacent components are undesirable because they lead to large temperature gradients. For example, consider the idealized lens barrel shown in Figure 2. We evaluate the time constant in Equation 2 for a $m = 10$ kg aluminum barrel ($k = 164$ W m$^{-1}$ K$^{-1}$, $C = 962$ J kg$^{-1}$ K$^{-1}$) with radius 0.15 m and cross-section $A_x = 0.004$ m$^2$.

The time constant for heat to conduct halfway around the lens barrel (e.g. from a focus motor, shown as $Q_{\rm gen}$ in Figure 2) is $\tau_{cond} = 1.9$ hours. If the interior of the lens barrel is filled with $m = 40$ kg of glass lenses ($k \simeq 0.95$ W m$^{-1}$ K$^{-1}$, $C \simeq 650$ J kg$^{-1}$ K$^{-1}$), the time constant for heat to conduct through the surface area $A = 0.1$ m$^2$ to the lens center, $L = 0.15$ m, is $\tau_{cond} = 11$ hours. Because the lens barrel time constant is $\sim$6 times faster than the lenses it supports, we use the lens barrel as a boundary condition in our lens studies rather than including it in the detailed models. We note that a radial temperature gradient will result in the lenses if the lens barrel rapidly changes temperature.

Internal temperature gradients in an instrument can be minimized if all the internal parts are designed to have short time constants, but this is difficult in practice because the internal parts (especially large refractive optics) have significant mass. Instead, an instrument can be heavily insulated to reduce the amplitude and time scale of temperature gradients. This is the approach we take with Binospec. Image quality is maintained if thermally induced de-focus and image drift are insignificant over the time scale of a single observation ($\sim$1 hr for a multi-object spectrograph like Binospec).

## 3. ENVIRONMENT

The thermal environment of an instrument must be well understood. Binospec is a Cassegrain-mounted instrument, and so we look at temperatures recorded in the MMT telescope dome. Figure 3 plots temperatures recorded between 27 April and 6 June 2001[6] from which we identify "moderate" and "extreme" thermal environments. The moderate thermal environment has ambient temperature changes by up to 8 °C over 48 hours. The extreme thermal environment has ambient temperature changes by up to 17 °C in 24 hours. By comparison, these thermal environments are approximately 60% larger than those recorded on Las Campanas.[7]

We find that temperature changes and temperature gradients inside an instrument scale linearly with the external temperature variations. For the case of Binospec, internal temperature gradients double with respect to the moderate and extreme thermal environments.

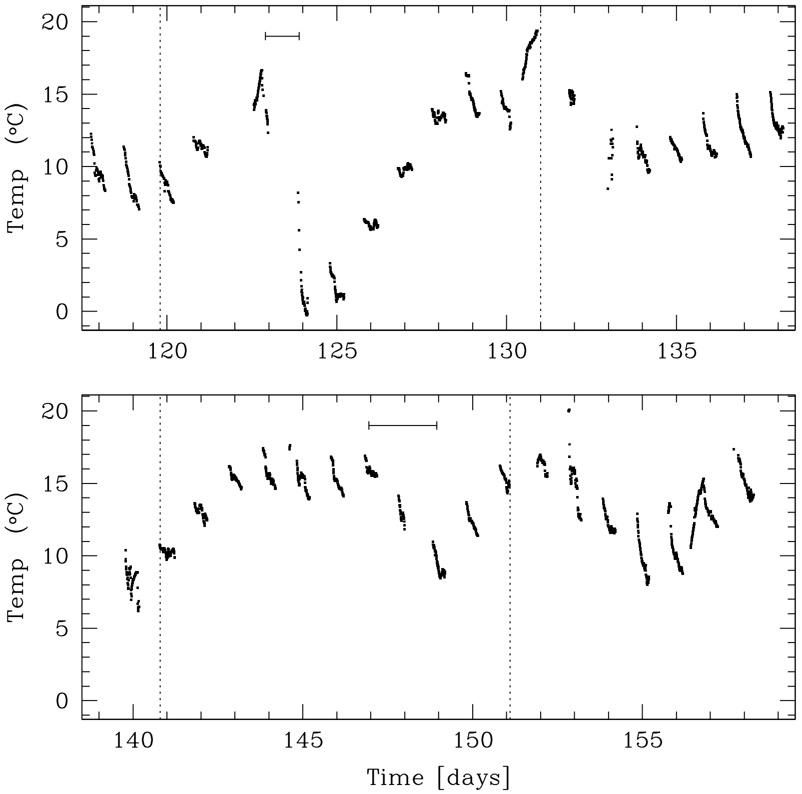

**Figure 3.** Temperatures recorded in the MMT telescope dome between 27 April and 6 June 2001. The bar in the upper panel shows an extreme 17 °C change in 24 hours. The bar in the lower panel shows a moderate 8 °C change over 48 hours. The dotted lines show the time intervals we used for the extreme (upper panel) and moderate (lower panel) boundary conditions. Most of the results we describe in the text refer to the moderate temperature conditions. The temperature gradients are a factor of two worse for the extreme conditions.

Varying the convection coefficient (i.e. wind speed) on the exterior of a well-insulated instrument has little effect on the net heat exchange between the instrument and the environment. This is because the exterior surface of a well-insulated instrument has a much faster time constant than its interior, and radiative heat exchange will balance convection, keeping the exterior in thermal equilibrium with the environment.

The night sky can be a significant heat sink and a source of diametral temperature gradients in an instrument. We have studied the effects exposing Binospec to the night sky. We use a view factor of 0.1, and assume the night sky is -100° C given the humidity and altitude of the MMT. We find that the optical bench would experience a maximum 0.3° C diametral temperature gradient with a 12 hr time scale. Finite element modeling shows that the resulting thermal deflection of the optical bench would cause negligible image shifts at the detector. However, temperature gradients in the optics are increased by 20% over the baseline Binospec model that has no radiation exchange with the night sky.

## 4. INSULATION

The greatest source of heat flow will dominate the thermal effects in an instrument. In this section we consider heat flow into an instrument through its 1) exterior insulation, 2) its mounting surface, and 3) its entrance window. Minimizing heat flow through these components is the key to properly insulating an instrument.

Binospec has a large surface area ($\sim$20 m$^2$), a quality shared by many modern astronomical instruments. The exterior of Binospec will be covered by insulated panels. To help us select an appropriate thickness of insulation, Table 1 displays the time constants of the optical bench and the maximum temperature gradients in the lens groups for 1.3, 2.5, 5.1, and 10.2 cm thick urethane foam insulation. Values are given for the moderate and extreme thermal environments. To minimize temperature gradients in the optics to the level of 0.1°, insulation at least 5.1 cm thick is required.

**Table 1.** The effects of insulation thickness on the Binospec thermal model. $\tau_{optb}$ is the time constant of the optical bench, $\Delta T_r$ is the largest radial gradient in the lens groups, and $\Delta T_z$ is the largest axial gradient in the lens groups. The moderate thermal environment has up to 8 °C ambient temperature changes over 48 hours; the extreme thermal environment has up to 17 °C ambient temperature changes over 24 hours.

| Insulation cm | $\tau_{optb}$ hrs | $\Delta T_r$ ° C | $\Delta T_z$ ° C |
|---|---|---|---|
| Moderate | | | |
| 1.3 | 13 | 0.18 | 0.21 |
| 2.5 | 20 | 0.15 | 0.17 |
| 5.1 | 30 | 0.12 | 0.14 |
| 10.2 | 43 | 0.10 | 0.12 |
| Extreme | | | |
| 1.3 | 13 | 0.43 | 0.54 |
| 2.5 | 20 | 0.33 | 0.40 |
| 5.1 | 30 | 0.24 | 0.28 |
| 10.2 | 43 | 0.17 | 0.19 |

Binospec is attached to the MMT with a mounting flange (see Figure 1) that is connected to the optical bench by graphite epoxy struts. In the baseline Binospec model, 30% of the peak heat flux between the environment and the spectrograph flows through these struts. If the conductivity of the graphite epoxy struts is not the isotropic value we assumed, but 3 times larger, then the heat flow along the struts is increased by 3 times and the time constant of the optical bench is reduced from 37 to 27 hrs. If the graphite epoxy struts are thermally isolated (e.g. by 1 cm thick Delrin pads), then the heat flow is reduced 4 times compared to the baseline model, and the time constant of the optical bench increases from 37 to 45 hrs. Thermally isolating the mounting flange from spectrograph bench is beneficial to the Binospec design.

One design decision is whether to include an entrance window on Binospec. The entrance window helps protect the instrument from dust and, moreover, helps insulate the instrument. The disadvantage of an entrance window is that its two air/glass surfaces reduce the throughput of the instrument. When the entrance window is removed from the baseline Binospec model, the optical bench time constant is reduced from 37 to 26 hours and the temperature gradients in the optics are increased 67% to 0.17° C. We conclude an entrance window is needed to effectively insulate Binospec.

## 5. INTERNAL HEAT SOURCES

Internal heat sources can have significant localized thermal effects in an instrument. The peak heat flow from internal motors in Binospec, assuming that the motors are powered only when they are required to supply torque, is ∼3 Watts. This is 10 times less than the peak heat flow with the environment in the baseline Binospec model, but sufficient to cause measurable local effects.

For example, Binospec may be operated in an imaging mode in which filter changes may occur frequently over the course of a night. Our models show that individual filter-changer motors with a 3% duty cycle (one filter change every 5 minutes) will warm by ∼2° C. Time constants inside the instrument are long, so there are no temperature transients in the optics, but there are gradually increasing temperature gradients in the optics.

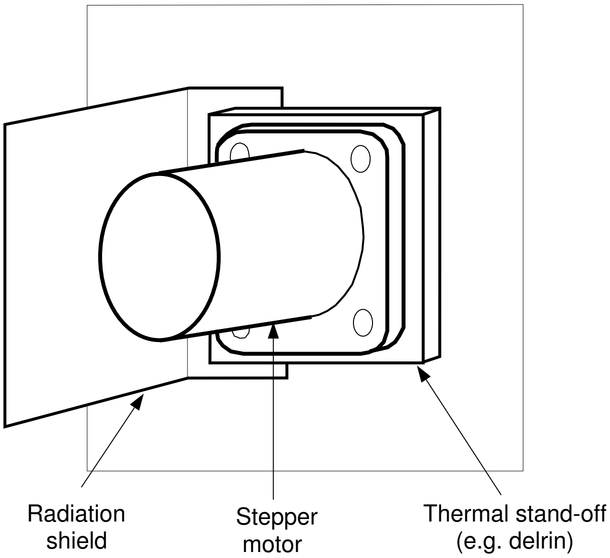

**Figure 4.** An example motor mounted with a thermal stand-off and radiation shield.

The axial temperature gradient in the collimator lens group 1 will increase by 0.02° C over 4 hours for a 3% duty cycle. It requires a duty cycle in excess of 15% for the Binospec motors to produce 0.1° C gradients equal to those caused by the thermal environment.

We create a finite element model to assess the effects of a hot motor attached to the Binospec optical bench. We find that a 16 W motor powered with a 3% duty cycle will produce a 0.1° C hot spot and a local 0.2 arcsec deflection of the optical bench. The hot spot has a time constant of ∼1 hr. If this hot spot is adjacent to a sensitive optical mount, such as the grating assembly, then a 0.03 pixel $\mathrm{hr}^{-1}$ image drift rate will result. This image drift rate is as much as we expect from the overall deflection of the Binospec optical bench due to the thermal environment.[1]

We thermally insulate motors from the Binospec structure with thermal stands-offs (e.g. Delrin pads) as shown in Figure 4. Thermal stand-offs reduce the heat flow and temperature transients by factors of ∼3, and allow radiation and convection to distribute the motor heat around the spectrograph. This will prevent any hot spots forming on the spectrograph bench. The disadvantage of thermal stand-offs is that motors will get correspondingly ∼3 times warmer.

Radiative heat transfer is proportional to the temperature to the 4th power, so radiation becomes important when a motor becomes hot. In Binospec we place radiation shields to block any line-of-sight to the optics (see Figure 4). A hot motor will also create a plume of hot air. Plumes may start air currents that will raise the convection coefficient in the instrument and quickly heat surrounding components. Care should be taken when placing hot motors below sensitive components, such as optics.

## 6. LENSES

Refractive optical systems are designed to be as athermal as possible, to avoid both loss of image quality and frequent re-focusing. Epps and Fabricant recently developed a powerful technique to athermalize refractive systems that takes advantage of the strong dn/dT of lens coupling fluid in multiplets.[5] The fluid coupling layers in Binospec lens groups are made into weak lenses that compensate for temperature changes. Epps and Fabricant show that 0.2° C radial temperature gradients in the Binospec lens groups will not significantly affect this athermal design.

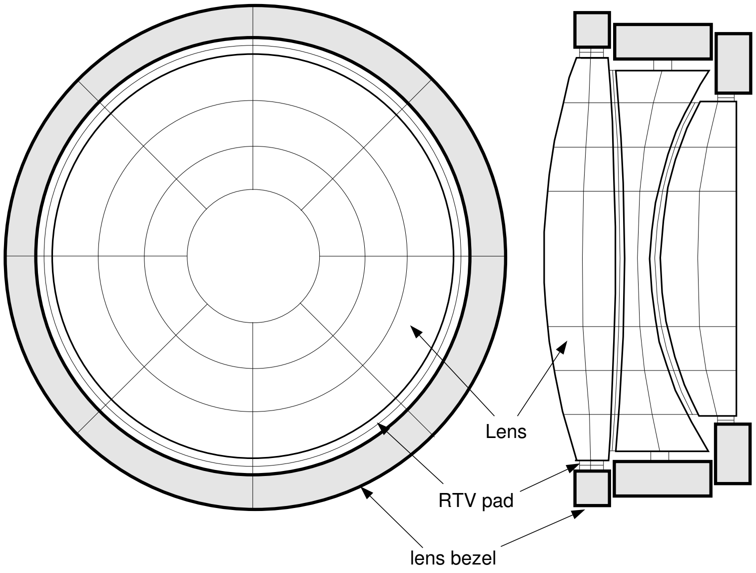

**Figure 5.** Our thermal model of Binospec camera lens group 3. Each optical element is divided into multiple axial, radial, and angular slices. Spaces between the lenses and the lens bezels are exaggerated to show the coupling fluid layers and the RTV bonds.

Responding to a suggestion by Brian Sutin, we have investigated how the coupling fluid affects the thermal characteristics of a lens group. The coupling fluid that we use in Binospec, Cargille Laser Liquid 5610, is an excellent insulator[8] ($k = 0.147$ W m$^{-1}$ K$^{-1}$) and will tend to thermally isolate the lenses in a lens group. We model the Binospec camera optics because they contain the majority of the "thick" ∼4 mm fluid layers. We note that the conductive thermal time constant is proportional to the thickness squared (Eqn. 2).

Figure 5 illustrates the lens group 3 portion of the detailed camera model. Spaces between the lenses, and the RTV layers connecting the lenses to the aluminum bezels, are exaggerated for clarity. The model boundary conditions are temperatures from our low resolution Binospec model. When we run the camera model with and without the coupling fluid layers present, we find that lens groups 1 and 2 have minimal $< 0.02°$ C increases in their axial and radial temperature gradients. However, lens group 3 has a 50% increase (to 0.15° C) in its axial and radial temperature gradient with the inclusion of the coupling fluid layers. This appears to be because the final element, a $CaF_2$ lens with conductivity $k = 9.71$ W m$^{-1}$ K$^{-1}$, becomes marginally isolated from the middle element, a NaCl lens with conductivity $k = 1.15$ W m$^{-1}$ K$^{-1}$ that is mounted on insulative flexures. When we double the thickness of the coupling fluid layers in the camera model, the axial temperature gradients in the lens groups increase by 10% to 20%. We conclude that the coupling fluid layers should be kept smaller than ∼5 mm in the Binospec optics to keep temperature gradients at a minimum.

## 7. OTHER CONVECTION ISSUES

Increasing the efficacy of convection inside an instrument can help equilibrate its components, reducing temperature gradients. We do not believe that fans are a good tool to increase convection inside an instrument because fans may be a significant internal heat source and thus drive larger temperature gradients than they alleviate. Instead, we investigate passive means to equilibrate an instrument.

The thermal deflection of the Binospec optical bench is largely caused by the difference in air temperature above and below the optical bench (Figure 1 shows how the Binospec optical bench effectively cuts the instrument in half). The optical bench would have 50% smaller temperature gradients in our models if the air temperatures above and below the optical bench are identical. We provide an ∼5 cm air gap between the optical bench and the exterior insulation to enable airflow between the upper and lower compartments.

The Binospec lens groups with the largest temperature differences are the middle lens groups, protected from convection and radiation with the instrument by the collimator and camera lens barrels. If we were to place ∼5 cm holes in the camera barrel to allow ventilation, our thermal model suggests that the lens group temperature differences would be reduced by 20%.

## ACKNOWLEDGMENTS

We thank Bob Fata and Jack Barberis for their important contributions to this project and Henry Bergner for providing the finite element model of the Binospec optical bench. Steve West kindly supplied the MMT dome temperature data. We thank Brian Sutin for pointing out that the lens coupling fluid may affect temperature gradients and time constants significantly. This work was supported by the Smithsonian Institution.

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