Optically-athermalized construction optical design for the IMACS Short camera

Harland W. Epps[1], and Brian M. Sutin[2]

[1] University of California Observatories/Lick Observatory
Santa Cruz, California 95064

[2] Observatories of the Carnegie Institution of Washington
Pasadena, California 91101

ABSTRACT

The optical performance of a large, optically fast, all-refracting spectrograph camera is extremely sensitive to potential temperature changes which might occur during an extended single observation, over the duration of an observing run, and/or on seasonal time scales. A small temperature change, even at the level of a few degrees C, will lead to changes in the refractive indices of the glasses and the coupling medium, changes in the lens-element geometries and in the dimensions of the lens cell. These effects combine in a design-specific manner to cause potential changes of focus and magnification within the camera as well as inherent loss of image quality.

We have used an optical design technique originally developed for the Smithsonian Astrophysical Observatory's BINOSPEC[1,2] instrument in order to produce a construction optical design for the Carnegie IMACS Short camera. This design combines the above-mentioned temperature-dependent parameter variations in such a way that their net effect upon focus and magnification is passively reduced to negligible residuals, without the use of high-expansion plastics, "negative-c.t.e." mechanisms or active control within the lens cell. Simultaneously, the design is optimized for best inherent image quality at any temperature within the designated operating range.

The optically-athermalized IMACS Short camera is under construction. We present its quantitative optical design together with our assessment of its expected performance over a (T= -4.0 to +20.0) C temperature range.

Keywords: lens, camera, spectrograph, IMACS, reimaging, athermalized, astronomy

1. INTRODUCTION

The Observatories of the Carnegie Institution of Washington (OCIW) is currently finishing a wide-field multi-object (slit) spectrograph and imager called IMACS[3,4] for the Magellan 1 telescope. IMACS will contain 2 separate cameras, a Long (focal length) camera which reimages at 9.00 pixels/arcsec and a Short camera which reimages at 5.00 pixels/arcsec. The IMACS cameras are unique in that they *share* a single interchangeable dewar containing an (8K x 8K) flat CCD-array with 15-micron pixels.[5]

The optics for the all-spherical Long camera have been completed. This paper will document the construction optical design for the double-aspheric Short camera whose optical fabrication is now nearing completion. Tucson Optical Research Corporation (TORC) has finished all of the spherical lens elements for the Short camera. Tinsley Laboratories is currently polishing the 2 aspheric lens elements which are scheduled to be completed (including their spherical sides) by the end of Summer 2002.

Nomenclature used in this paper is described by H.W. Epps.[6] The general characteristics of the IMACS Short camera are summarized here below for the reader's convenience.

1. The Short camera will accommodate direct imaging over traditional passbands within the (0.39 to 1.05)-micron spectral range and low- to moderate-dispersion, slit-coupled, multi-object, grism-dispersed spectroscopy.

2. The IMACS spectrograph has a 5.90-inch diameter collimated beam. The Short camera was optimized with a (6.35 by 7.62)-inch elliptical entrance pupil, located 4.50 inches ahead of the first lens element vertex, with the

longer dimension in the dispersion direction. This geometry was chosen so as to accommodate all of the various pupil presentations which the camera will experience in its various operating modes.

3. The Short camera has a 14.00-inch focal length, a 9.55-inch diameter entrance aperture and a 13.00-degree field radius which produces a 6.45-inch diameter flat field of view.

4. Provision is made for an optical filter within the Short camera. The filter is simulated in the construction optical design by a 12.0-mm thick plano-plano disk of Ohara @PBL25Y whose refractive index n(d)= 1.58144 and whose Abbe number V(d)= 40.8 (a typical medium-index, medium-dispersion optical glass).

5. The detector will be a CCD-array containing (8192 by 8192) 15-micron pixels. The dewar window will be a concave-plano Fused Silica lens and the back focal distance (b.f.d.) will be roughly 0.33 inches. The dewar/detector system must be *shared* between the Long and the Short cameras without modification. The Long and Short cameras were designed in tandem so as to satisfy this requirement. Since the Long camera optics are now finished, the Short camera construction design was constrained accordingly.

6. Monochromatic image analysis done in real-time (during the optical design process) and reported here is likely to represent upper limits to the expected rms image diameters because the camera will have been (purposefully) "over-driven" in almost all cases by the entrance pupil geometry described in Item 2 above. For example, the actual entrance pupil will a 5.90-inch diameter circle for all cases of direct imaging. The lateral chromatic aberration (lateral color) calculations will not be affected much by this circumstance.

It should be mentioned that during this study, all of the optical designing, the optimization and the real-time image analyses were calculated with HWE's proprietary code, OARSA. Encircled-energy (ray-count) analyses were calculated by BMS using his end-to-end IMACS numerical model and his own proprietary ray trace code. This provided a completely *independent* cross-check of the quantitative results.

2. IMACS SHORT CAMERA DEVELOPMENT HISTORY

The IMACS Short camera optical design was started in July 1996 with a study of possible configurations for a 12.75-inch focal length camera which would have led to a final imaging scale of 4.55 pixels/arcsec. However excessive lateral color effects and the desire to cover more of the (available) CCD detector array prompted project management to opt for a 14.00-inch focal length. Design studies at that focal length were started in January 1997, leading to the conclusion that a triple-aspheric [Doublet]/[Singlet]/[Triplet]/[Doublet]/{filter}/[Singlet]/[Window] configuration (similar to the DEIMOS lens for Keck 2) would be the best alternative. Subsequent calculations led to a *preconstruction design* Run No. 041597AM. It was reported in detail by H. W. Epps[7] and it was also described and documented (along with the DEIMOS preconstruction camera) by H. W. Epps.[6] Following approval by project management, optical glass was ordered for the IMACS Short camera based upon this design.

During Summer 1999, H. W. Epps and D. G. Fabricant[8] developed a new theoretical process for the BINOSPEC project of Smithsonian Astrophysical Observatory (SAO) which enabled an optical system to be designed in such a way that it would be *passively athermalized* without resort to the use of mechanical control, "negative c.t.e. mechanisms" and the like. This process, which we call Optical ATHermalization (OATH) is described in more detail in Section 3 and Section 4. It relies upon the use of "*coupling-fluid lenses.*" These are formed by allowing (substantial) differences of radius across each of the fluid-coupled lens-element interfaces. It seemed appropriate to apply the OATH process to the IMACS camera designs even though they were already approaching their respective construction phases. OATH did not prove useful for the Long camera because it lacked sufficient coupling interfaces. However it ultimately proved to be quite beneficial in the Short camera.

The Short camera design evolved as the melt-sheet indices of refraction for the real optical glass were received and fluid-coupling was introduced to replace the Dow Corning Q2-3067 optical couplant ("grease") which had been used for the preconstruction design. Further modifications followed as the radii of the coupled lens-interfaces were allowed to become substantially different from each other during the athermalization process. This actually led to a *lens-grouping change*, the *removal* of one lens element as well as the *elimination* of one of the aspheric surfaces from the preconstruction design! This is an extremely rare circumstance which virtually never happens after the optical glass for construction of a particular design has been delivered.

The chronology of the IMACS Short camera development is best documented in terms of a series of design "Runs," each of which represents the culmination of a particular phase of the optical design. These Runs are identified, together with a description of the advances represented by each of them, and are reported by H. W. Epps.[9]

3. THEORETICAL BASIS FOR PASSIVE OPTICAL ATHERMALIZATION (OATH)

The optical performance of a fast spectrograph camera is expected to be sensitive to thermal deviations from its nominal (equilibrium) environment because it is well known that: 1) The refractive indices of the optical materials are functions of temperature; 2) The coefficients of thermal expansion (c.t.e.'s) of the glasses will cause their radii, aspheric coefficients and thicknesses to be functions of temperature; and 3) The lens cell material(s) and mechanical design may cause the inter-group lens spacings to be functions of temperature also. In practice, all of these three effects can be of comparable magnitude such that none of them can be ignored. The *three main consequences* of a temperature change within a fast spectrograph camera are that: 1) It will likely go out of focus; 2) Its transverse magnification will likely change such that non-central images would become blurred even if the camera remained in focus; and 3) the camera's inherent image quality may be compromised after it is refocused as well as possible for a different temperature. By Optical ATHermalization, we mean that the optical system is designed such that its focus and its transverse magnification will be *passively invariant* to substantial (quasi-equilibrium) deviations from its nominal operating temperature and that the design will retain its inherent image quality.

The idea that OATH might be possible in an optical system rests upon the fact that whereas the thermo-optical coefficients (dn/dT) for *most* (but not all) optical glasses are *positive* numbers of roughly a few parts in 10ˆ-6 per deg C, the corresponding numbers for typical optical coupling fluids are *negative* and perhaps 100 times larger in magnitude. Thus it would seem plausible that if the coupling interfaces were allowed to become relatively low- to modest-power "fluid lenses," they would potentially have substantial impact on the system's thermal behavior (in a counteracting sense) but at the same time, have little (but probably non-negligible) impact upon the optical design itself. Thus one might hope to be able to optimize the design such that it would be passively athermalized and at the same time, would achieve optical imaging and lateral color correction comparable to (or even better than) a conventional optical design for the same type of system operating at its design temperature only.

In order to proceed with a theoretical treatment, it was necessary to make some assumptions about the detailed nature of the thermal perturbations as well as the details of the lens cell design. It would seem almost hopeless to attempt to model and to compensate an arbitrary thermal pulse through the system and such a pulse would seem unlikely at any rate, in any practical system. Thus it was assumed that whereas the lens system may undergo a substantial temperature change during its operation, it does so in such a way that it is *always in quasi-equilibrium.*

The lens cell design is a less obvious situation as there could potentially be several different mechanical design options which might be competitive with each other but which would lead to different conclusions regarding the inter-group lens spacing changes they would cause as the result of a temperature change. Thus in order to make progress, it became necessary to choose one lens cell concept (arbitrarily). Since extensive mechanical design and analysis work had already been done by R. G. Fata and D. G. Fabricant[10] on the lens cells for the BINOSPEC collimator(s) and camera(s) and since the OATH process was originally developed for BINOSPEC, that lens cell concept was chosen as a basis for the analysis.

The BINOSPEC lens cell concept assumes that each lens element is mounted within an annular metal ring (a bezel) using an elastomer (such as Sylgard-184) to fill the gap between the lens girdle and the metal. The bezels for each lens element are stacked together with metal spacers between them whose thicknesses are chosen so as to provide the correct lens-element spacings at the nominal design temperature. All of the bezels and spacers are inserted within an outer metal tube and compressed together with a compliant force (provided by springs of some appropriate type).

It is assumed that the *location* of each lens element is then determined by the mid-plane passing through the half-thickness point(s) on its metal bezel. All of the metal is assumed to be of the same type, say aluminum as an example. Thus if the temperature changes, it becomes a tedious but straight forward matter to determine the resulting changes in the inter-group lens spacings as well as those within each of the fluid lenses.

4. IMPLEMENTATION OF OATH INTO THE OPTICAL DESIGN PROCESS

Any optimization process must be defined in terms of a quantitative (or at least objectively determinable) *criterion* by which it can be decided whether or not a given alternative (optical system) is preferable as compared with another alternative. This criterion is usually a combination of many *physical parameters* related to image quality, wavelength coverage, field angle, path-length errors over the pupil, etc., as well as *constraints* having to do with the configuration geometry, the magnitudes of maximum aspheric deviations (MAD's), pupil location(s), distortion and the like. The construction of this criterion and its computational application so as to predict, evaluate and verify that one has achieved an optimal solution, is itself a rather arcane problem in applied mathematics which is far beyond the scope of this paper. Suffice it to say that in practice, it is possible to develop a *demerit function* whose evaluation for a given system provides a single positive numerical value which decreases monotonically as that system improves in its overall performance. It is also possible to construct a sophisticated formalism which is predictive, such that the selection of systems to evaluate is very far removed from trial and error.

In principle, an optical system which must operate over a wide range of temperatures can be thought of as a multi-configuration system, such as a telephoto lens. Thus conceptually, the implementation of the OATH process into OARSA is quite direct, though exceedingly complicated in practice. One begins by computing the demerit function and the associated predictive formalism in the normal fashion (for the given nominal operating temperature). One then thermally perturbs the system which is under evaluation, to the maximum (and subsequently to the minimum) allowed temperature(s) "on the fly" and does all of the computations again. The demerit function(s) are added in quadrature (with weighting functions as may be appropriate) and the predictive formalism is cross-correlated to determine a "best-alternative strategy" for continuing with the optimization. Penalties are applied to the demerit function to mitigate against change of focus and change of lateral magnification with change of temperature, so as to drive the optimized solution toward an athermalized state with acceptable optical quality over the full thermal range.

Each optimization Run proceeds until the resulting (multi-thermal) demerit function reaches a (local) minimum. The rms image diameters averaged over all field angles and wavelengths (without refocus) are then calculated in real-time for the "final" system (computed by that particular Run) and the maximum rms lateral color is also determined. All of these image characteristics are evaluated at the nominal operating temperature only. In addition, a calculation is made which determines the expected change of focus with temperature (in units of real inches) and the percentage change in the lateral magnification. Both of those changes are determined as algebraic difference quantities, for the maximum (and minimum) temperature(s) relative to the nominal temperature. All of this information is available to the designer on a momentary basis from Run to Run.

When it appears that an attractive solution has been found, more detailed ray trace modeling of the full end-to-end system is calculated with an independent code which is used to analyze system performance over the full operating temperature range. In the case of the IMACS Short camera, BMS provided this detailed evaluation using his own proprietary ray trace code.

5. MELT-SHEET OPTICAL GLASS AND CARGILLE COUPLING FLUID

The lens elements in the Short camera are identified as L1, L2, etc., and they are designated in the computer by the corresponding abbreviations ..SHOR01, ..SHOR02, etc. Prefixes, such as "_8" or "_C" or "_H" mean "real optical material" at +8.0 C or -4.0 C or +20.0 C, respectively. The original lens-element configuration in preconstruction design Run No. 041597AM contained a lens element L6 which was eliminated in later designs, as described in Section 2. However the lens element numbering was not changed. Thus, L6 (..SHOR06) is simply *absent* in construction design Run No. 030201AY.

Melt-sheet refractive index data were received from Ohara Corporation for all of the Short camera (optical glass) lens blanks. These include six-place measurements made at a given temperature (around +25.0 C) for each melt type, at each of the 10 standard wavelengths within the (0.365 to 1.014)-micron spectral range. These indices were transformed to the stipulated nominal operating temperature of T= +8.0 C and to other temperatures as needed using Ohara catalog values for the thermo-optical coefficients (dn/dT).

The calcium fluoride (CaF_2) is modeled by HWE's standard CAF2 Schott coefficients at T= +20.0 C and it was transformed to other temperatures as needed using thermo-optical coefficients derived by D. G. Fabricant of SAO from information given by A. Feldman, et al.[11] The Fused Silica is modeled by HWE's standard FSILICA Schott coefficients at T= +20.0 C and it was transformed to other temperatures as needed using the thermo-optical coefficients given graphically by I. H. Malitson.[12]

The real coupling fluid will be taken from a large quantity of Cargille Type 5610, n(D)= 1.500 (nominal) which has been purchased for use in IMACS. The refractive indices for this fluid were measured by Ohara Corporation for (T= -4.0, +2.0, +8.0, +14.0 and +20.0) C, at 9 standard wavelengths in the (0.405 to 1.014)-micron spectral range. They were also measured for (T= +18.0, +20.0 and +22.0) C, at 0.365, 1.129 and 1.530 microns. The measurement precision was estimated to be better than 1.0^-4 and the temperature stability was held within +/- 0.1 deg C. These data were fitted globally as a function of temperature and wavelength by BMS. We refer to this coupling fluid informally as "Brian's oil," although it is clearly anything but a typical hydrocarbon-based oil in the chemical sense. It is described by Cargille Laboratories Inc., as being a siloxane-based fluid.

All of the index data sets so derived were fitted to a Schott-formula for each individual case by the method of least squares. The fitting coefficients for each of the lens blanks and for the Cargille coupling fluid are given in Table 1 at T= +8.0 C (the nominal operating temperature), at T= -4.0 C (the "cold" limit) and at T= +20.0 C (the "hot" limit). The melt identification(s) for the optical glass(es) are also given in Table 1.

All of these Schott coefficient representations taken together codify the measured refractive behavior of all of the materials which are actually being used in the construction of the IMACS Short camera, including the all-important dependence of the refractive indices on temperature. It can be seen that the thermo-optical coefficients for the Cargille coupling fluid have second- (and likely higher)-order derivatives about the nominal T= +8.0 C operating temperature which *are not zero.* It is suspected that these derivatives ultimately limit the thermal range over which OATH can be achieved in a given optical system. We apologize for the morass of numbers in Table 1 but without them, the Short camera's construction design can not be represented in a way that would enable the reader to evaluate its optical performance and its thermal behavior quantitatively.

6. ATHERMALIZED SHORT CAMERA CONSTRUCTION DESIGN RUN NO. 030201AY

As the Short camera's athermalization proceeded, the lens-grouping change mentioned in Section 2 led to a double-aspheric [Doublet]/[Singlet]/[Quartet]/{filter}/[Singlet]/[Window] configuration. A representative preliminary model, Run No. 100799AH, had MAD's which were (0.0291 and 0.0221) inches. It contains a mildly curved convex meniscus fluid lens in the leading [Doublet] and 3 more substantially curved fluid lenses within the [Quartet]. Its (real-time) monochromatic rms image diameters were 24.6 +/- 7.2 microns averaged over all wavelengths and field angles (without refocus), with 19.6 microns of maximum rms lateral color. The athermalization code estimated (during the design process) that over the full (T= -4.0 to +20.0) C operating temperature range, a focus variation of +/- 0.0005 inches and a transverse magnification variation of +/- 0.012% would be expected. Independent ray trace calculations by BMS showed focus and magnification performance which confirmed these results, thus validating the athermalization procedure described in Section 4. This design demonstrated clearly that an athermalized version of the double-aspheric configuration was possible. However there remained the questions of whether or not the aspheric amplitudes could be reduced and whether or not the optical power contained in each of the fluid lenses could be reduced.

Tucson Optical Research Corporation (TORC) was chosen as the optical manufacturer for the spherical lens elements but considerable time passed as project management explored options for the production of the 2 aspheric lens elements. It was decided to incorporate as many of the standard TORC test-plate radii as possible into the design as a cost saving measure but the (spherical sides of) the aspheric elements were not constrained because a qualified manufacturer had not yet been identified as the time approached to finish the actual construction optical design.

During the last phase of the design, TORC standard radii (at T= +25.0 C) were introduced (with corrections to T= +8.0 C). It proved possible to use them for *all but one surface* in the spherical lens elements. An (unsuccessful) effort was made to reduce the MAD's and to reduce the optical power in the fluid lenses within the [Quartet]. This led to the final athermalized construction design Run No. 030201AY with MAD's which are (0.0291 and 0.0230) inches. Its fully quantitative system prescription (at nominal T= +8.0 C operating temperature) is given in Figure 1 which also shows a scaled drawing of the design by Dr. Bruce Bigelow of OCIW. Note that the lens element diameters shown in the column marked "CLR DIA" are (approximate) optical clear apertures. They are *not* the intended mechanical finished diameters (which are usually somewhat larger than optical clear apertures).

This design shows some 0.31% barrel distortion which is acceptable. Its nominal b.f.d. is some 0.33556 inches which very nearly matches the b.f.d. of the final As-Built02 Run No. 052601AG for the IMACS Long camera, which is 0.33543 inches. The (real-time) monochromatic rms image diameters were 24.2 +/- 6.7 microns averaged over all wavelengths and field angles (without refocus), with 20.5 microns of maximum rms lateral color. The real-time athermalization analysis indicated that over a (T= -4.0 to +20.0) C operating temperature range, a focus variation of +/- 0.0002 inches and a transverse magnification variation of +/- 0.014% would be expected. These values are based on assumptions that the lens cell design conforms to the description given in Section 3 and that during any thermal perturbation, the camera always remains in quasi-equilibrium.

The end-to-end system, consisting of the Magellan 1 telescope, its field corrector, the IMACS collimator and the construction Run No. 030201AY Short camera, was ray traced independently by BMS. His calculations included 10 individual wavelengths covering the (0.39 to 1.05)-micron spectral range and 10 field positions distributed uniformly from on-axis to the extreme edge of the corrector's (somewhat vignetted) 15.0-arcmin field radius. The resulting matrix of (10 x 10) individual ray traces was computed at 1.0 deg C intervals as the camera's temperature was slewed in 1.0 deg C steps over a (T= -4.0 C to +20.0) C range (while all the other optics in the system remained at fixed temperature). The rms value of the 80%-energy image diameter, averaged over a given (10 x 10) matrix of images, varied monotonically from d(80)= 34.8 microns at T= -4.0 C to d(80)= 33.7 microns at T= +20.0 C. These averages only improved by a few percent when the camera was refocused for each individual temperature. The full range of focus motion was only about +/- 0.00045 inches. The transverse magnification variation over the same temperature range was calculated to be +/- 0.015% or roughly +/- 0.66 pixels at the edge of the full 15.0-arcmin field radius. These detailed ray traces include the residual aberrations of the telescope, field corrector, and collimator. The results are fully consistent with the real-time predictions by OARSA during the camera optimization and they further serve to validate our procedures.

The dominant residual aberration in Short camera Run No. 030201AY is axial color (old-fashioned "chromatic aberration") which is shown in Figure 2. The peak-to-valley amplitude of this effect is some 0.0046 inches and its rms value is 0.0017 inches, over the (0.39 to 1.05)-micron spectral range. This is a residual artifact of the dispersion curve of CaF_2, an essential material which appears in almost all high-performance spectrograph camera designs and which cannot be eliminated with any practical combination of reasonable uv-transmitting optical glasses. Its undesirable effects are pronounced in the on-axis to mid-field imaging over the (0.70 to 0.86)-micron spectral range. These effects can be mitigated effectively by moving the CCD outward (away from SHOR09) by perhaps 0.0015 inches. However doing so will soften the imaging in the blue spectral range. This refocusing may not be practical for lowest-dispersion spectroscopy but it almost certainly will serve to sharpen the images in direct-imaging mode wherein the traditional passbands are not nearly so wide. The actual 5.90-inch diameter (round) entrance pupil which will illuminate the camera for direct imaging should also help to sharpen the images in this mode.

It is assumed that high efficiency antireflection (AR) coatings will be used on all exposed optical surfaces. This is essential to maximize throughput and to avoid potential ghost images and ghost pupils by back reflection (off of the detector in particular). Every attempt has been made to mitigate such unwanted ghosts by careful choice of lens-element radii during the design's development, although at some residual level they cannot be avoided.

7. COUPLING FLUID THERMAL PERTURBATION RESPONSE TIME

One major concern is the effect of rapid temperature changes (on a time scale of perhaps half-an-hour or less). Since the thermo-optical coefficients (dn/dT) for the Cargille coupling fluid have large amplitudes, *thermal gradients* induced into the fluid could potentially result in significant image degradation.

The thermal time constant of a thin sheet of material is given by $w^2 C_p d/k$, where w is the width of the sheet (or half-width, if it is heated from both sides), C_p is the heat capacity, d is the density, and k is the thermal conductivity. Since the thermal time constant is proportional to the square of the sheet thickness, very thin sheets do not pose thermal problems. Our main concern is the central region of the last fluid lens in the [Quartet] which is excessively (but unavoidably) thick. The half-width of that region is roughly 0.35 inches which suggests a thermal time constant of almost an hour. A finite element thermal analysis calculated by Dr. Bruce Bigelow of OCIW confirmed this estimate quantitatively and he determined that at least 1 to 2 inches of insulation thickness would be required to protect the Short camera from rapid thermal changes which might realistically be anticipated at the telescope.

8. CONCLUSION

The OATH design process for optical athermalization[8] was developed specifically for SAO's BINOSPEC project. The construction designs for its (pair of) collimator(s) and camera(s) are nearing completion. However to the best of our knowledge, the IMACS Short camera represents the *pioneering effort* to actually produce a *passively athermalized* high-performance optical system using fluid lenses incorporated into the optical design itself so as to accomplish the athermalization. Fluid lenses have been used in the past for chromatic correction because the anomalous dispersion characteristics found in some fluids lend themselves to that purpose. However, the usefulness of such designs has been limited to nearly isothermal environments by the resulting extra sensitivity to thermal perturbations. In the IMACS Short camera (and in the BINOSPEC optics soon to follow), the chromatic correction potential as well as the thermo-optical sensitivity of the coupling fluid have *both been put to positive use* in order to achieve the desired broad passband capabilities as well as the remarkable passive athermalization.

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