Low Distortion Lens Design for Large Scintillators

Robert M. Malone, Daniel K. Frayer, Morris I. Kaufman, Paul K. Manhart

National Security Technologies, LLC, New Mexico Operations, Los Alamos,
2900 East Road, Los Alamos, New Mexico, 87544, USA, malonerm@nv.doe.gov

D. Cort Gautier, James F. Hunter, Brandon M. Lattimore, Kelley G. Vansyoc

Los Alamos National Laboratory, P.O. Box 1663, Los Alamos, New Mexico 87544, USA

Abstract: Tomographic imaging of large objects from an x-ray source require a 240 mm square scintillator that is imaged onto a 90 mm square CCD with <0.01% distortion. A large pellicle and internal folding mirror keep the optical elements and the CCD camera out of the x-ray beam path to minimize shielding requirements.

OCIS codes: (080.2740) Geometric optical design; (080.3620) Lens system design

1. Introduction

Better imaging is needed for 2-D digital radiography and computer tomography (3-D) on the Los Alamos National Laboratory's Microtron x-ray–generating source, a bremsstrahlung source with endpoint energies of 6, 10, 15, and 20 MeV. Large objects are placed into the x-ray beam and rotated between radiographs. X-rays are deposited into scintillators that are viewed with digital cameras. Better light gathering is needed because the scintillators emit low levels of light. Earlier imaging techniques used film in contact with the scintillator. Our design goal is to match the resolution of the digital camera system to that of the film. 3-D tomography requires extremely low distortion of the collected images.

2. Optical Design Specifications

The original design intent for the Los Alamos National Laboratory's Microtron x-ray source is for a 9000 × 9000 pixel CCD camera configured in a 90 × 90 mm square format. As we await delivery of this camera, initial testing is being done with a 4000 × 4000 pixel CCD camera viewing a smaller field of view. Tomographic image reconstruction requires extremely low distortion and is the driving constraint in the optical design. For the 9000 × 9000 CCD, we desire not more than a half-pixel distortion in the center and less than one pixel at the edge. Optical materials are not allowed to fluoresce from scattered x-rays.

The starting point for this optical design is an eleven-element zoom lens used for the Cygnus x-ray source [1,2]. This large telecentric zoom lens system views a blue-emitting lutetium yttrium orthosilicate $Lu_xY_{2-x}SiO_5$:Ce (LYSO) scintillator measuring 200 mm square. Because the LYSO scintillator thickness could range from 2 to 10 mm, this zoom lens design incorporated telecentricity to minimize field-dependent blur induced by finite scintillator thickness. This zoom lens system has moderate distortion that has to be continually mapped out with image processing software.

Based on the Cygnus zoom lens system, our starting optical design (Figures 1 and 2) has telecentric light collection. Our new design views a 1 mm thick red-emitting scintillator, which allows more choices from among available glass materials. The scintillator material for this design is an Eu-doped Gd-Lu-Bixbyite (GLO), developed at Lawrence Livermore National Laboratory [3].

Next, aspheric curvatures were modeled on several different surfaces. However, tolerancing on an aspheric surface would not satisfy our distortion limits. Therefore, the design was relaxed to be as close to telecentric as reasonable. This adjustment made the distortion specification easier to achieve. The desired modulation transfer function (MTF) for the 9000 × 9000 pixel camera exceeds the requirement of 50 lp/mm resolution. Figure 3 shows that we did not meet the distortion specification. This specification required <1 pixel at the edge of the camera. Pixels are 10 microns square. For a 90 mm square–sized camera, 1 pixel of distortion converts to 0.02% distortion. Figure 3 shows a distortion value of 1.2% at the edge of field.

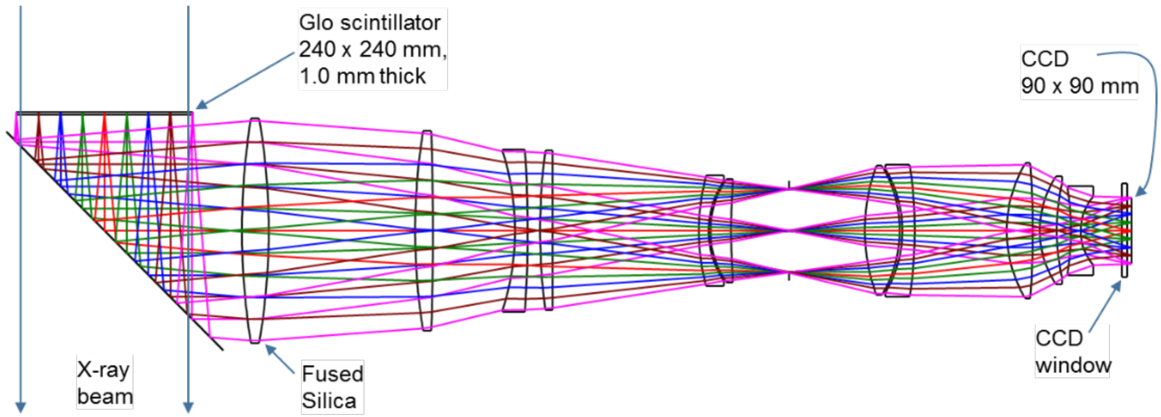

Fig. 1. Initial optical design. Telecentric light collected at 0.09 NA. Air-spaced doublet lenses are used.
No distortion specifications have been corrected.

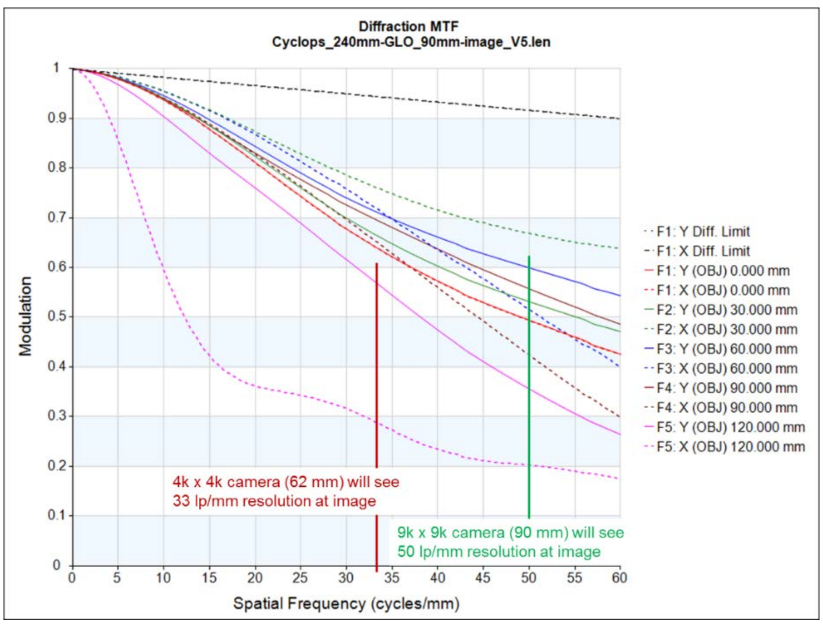

Fig. 2. Initial optical design. A smaller CCD camera will test the lens design with 4000 × 4000 pixel resolution,
until the 9000 × 9000 pixel camera arrives. Resolution requirements are met.

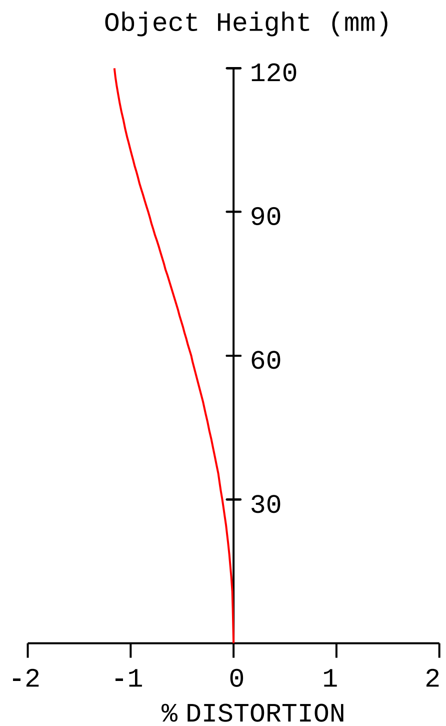

Fig. 3. Initial optical design. Distortion values do not meet specifications.

2.1 Optical Design to Minimize Distortion

Further design criteria were added to the optical design (Figures 4 and 5). The glass materials have been labeled in Figure 4. The optical elements and the CCD must be located out of the x-ray beam and into enclosures that can be shielded. A large pellicle has to extend away from the scintillator, and an internal folding mirror makes the design footprint more compact. An algorithm was written for the optimization routine that controls the absolute value of the distortion at each field point. Values for the field distortion were gradually reduced during each iteration of the optimization. The ray tracing would fail if the distortion values were reduced too quickly. The stop surface has the same curvature as its following lens surface.

Two cemented doublets are used and are located on both sides of the stop position. Making them into air-spaced doublets also works. But, having surfaces separated by 2 mm with identical curvatures would increase the background ghost light levels at the image plane. Analysis was done on cemented doublets that was presented at this conference [4].

This design achieved excellent distortion values (Figure 6). However, after checking with glass vendors, one cannot get some of these glass materials in the diameters and thicknesses we desire.

The spectral emission of the GLO scintillator is shown in Figure 7. It shows unusual emissions at wavelengths away from its peak emission. Better resolution could be achieved by filtering out wavelengths above 660 nm. This adds two more surfaces that would contribute to background scatter. So, this filter has not been considered yet.

2.2. Optical Design Sets Correct Glasses Before Distortion Optimization

Because the stop aperture has the same curvature as its following lens surface, the mount for this lens element will contain the stop aperture. We had to reduce resolution expectations to make the lenses thinner; thinner lenses also tightened lens elements tolerancing Next, glass materials were selected before distortion algorithms were applied. The current design is shown in Figures 8–10. The new glass materials have been labeled in Figure 8. Tolerancing has not been completed at the writing of this paper.

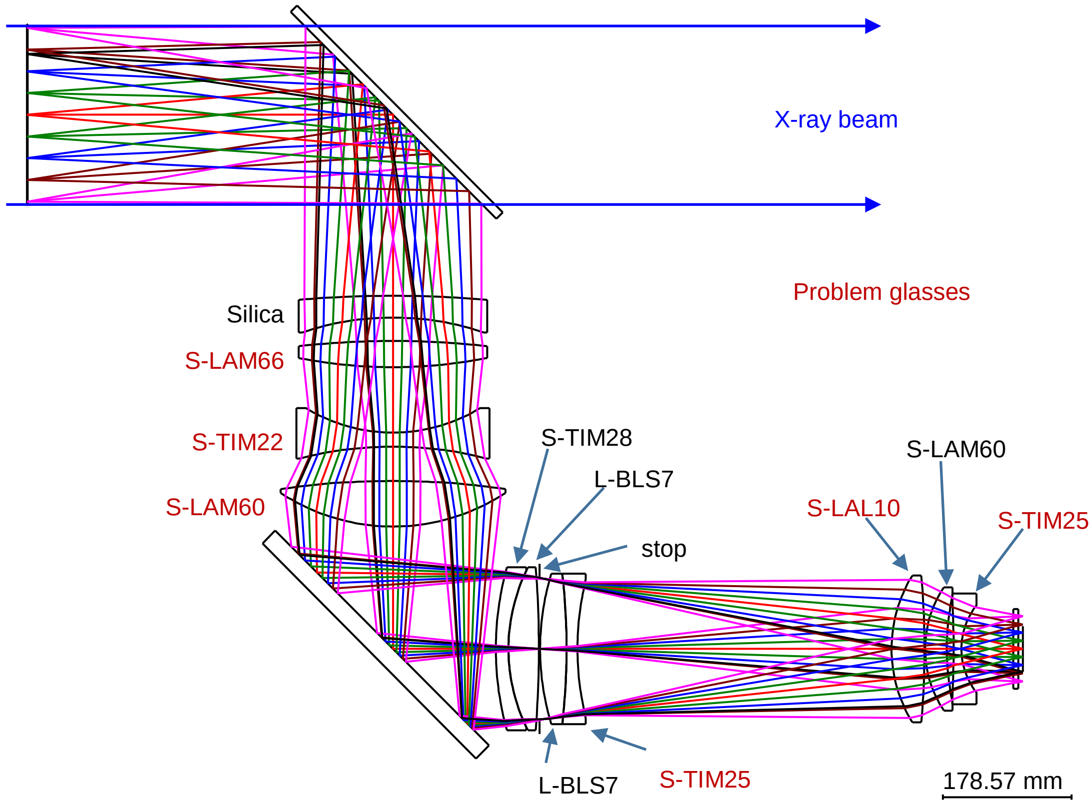

Fig. 4. To keep optical elements out of the x-ray path, a large pellicle and internal folding mirror are used to place the CCD camera (not shown) in a shielded location. The two doublets are cemented.

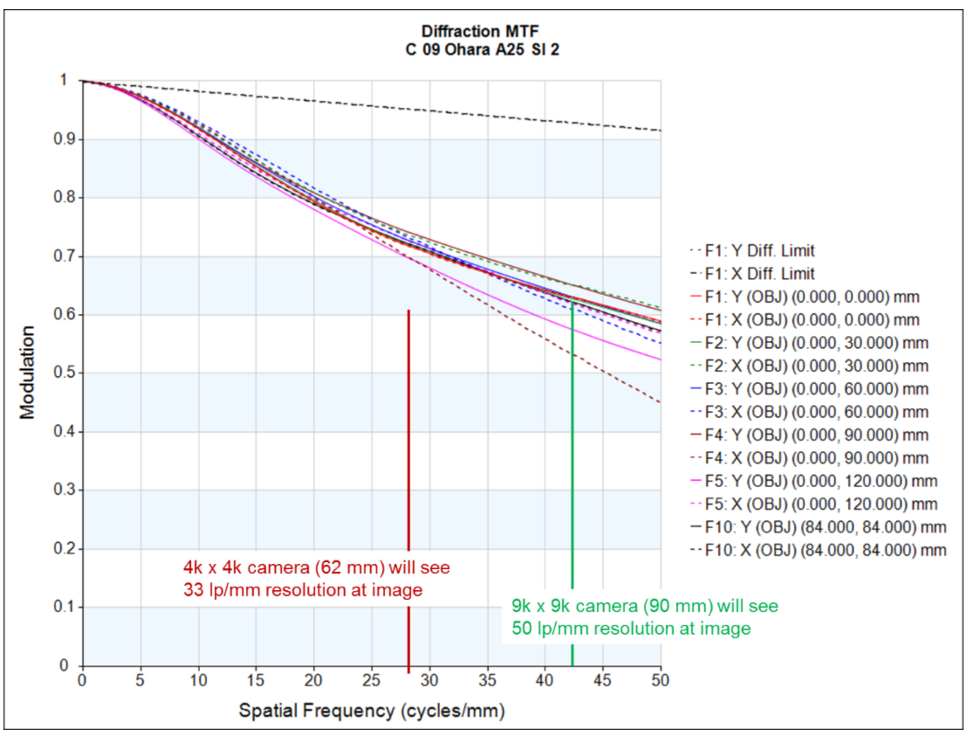

Fig. 5. We have achieved good resolution

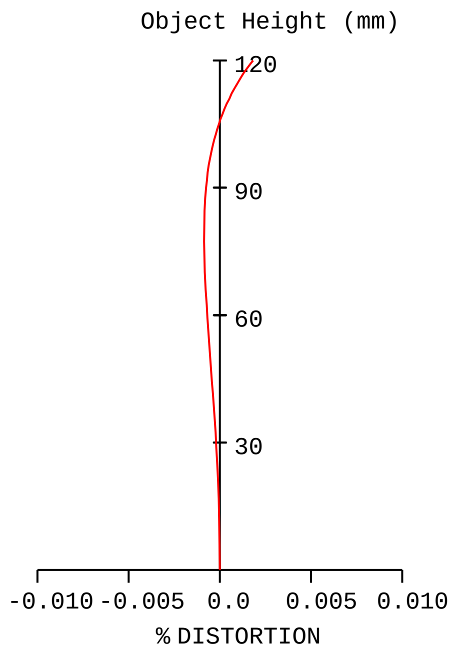

Fig. 6. We have achieved the distortion requirement. The distortion scaling has changed considerable from Figure 3.

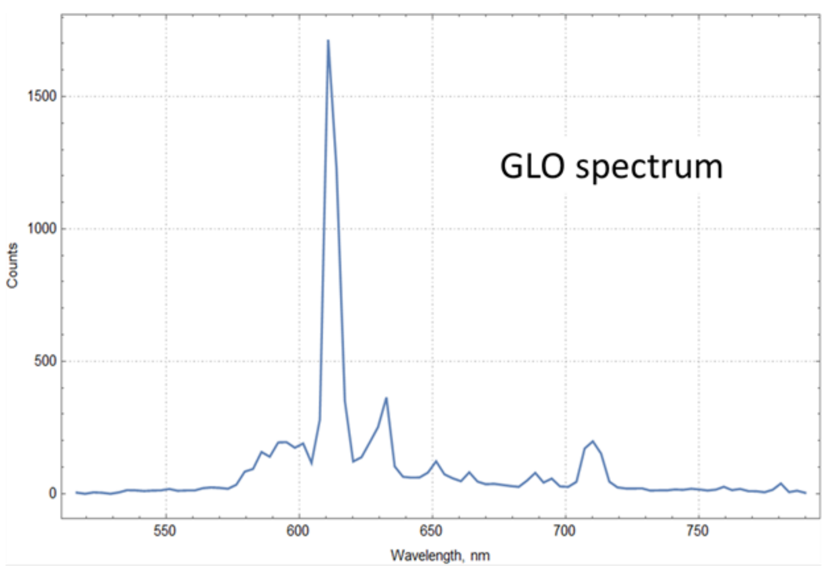

Fig. 7. Wavelength spectrum of the GLO (Eu) scintillator

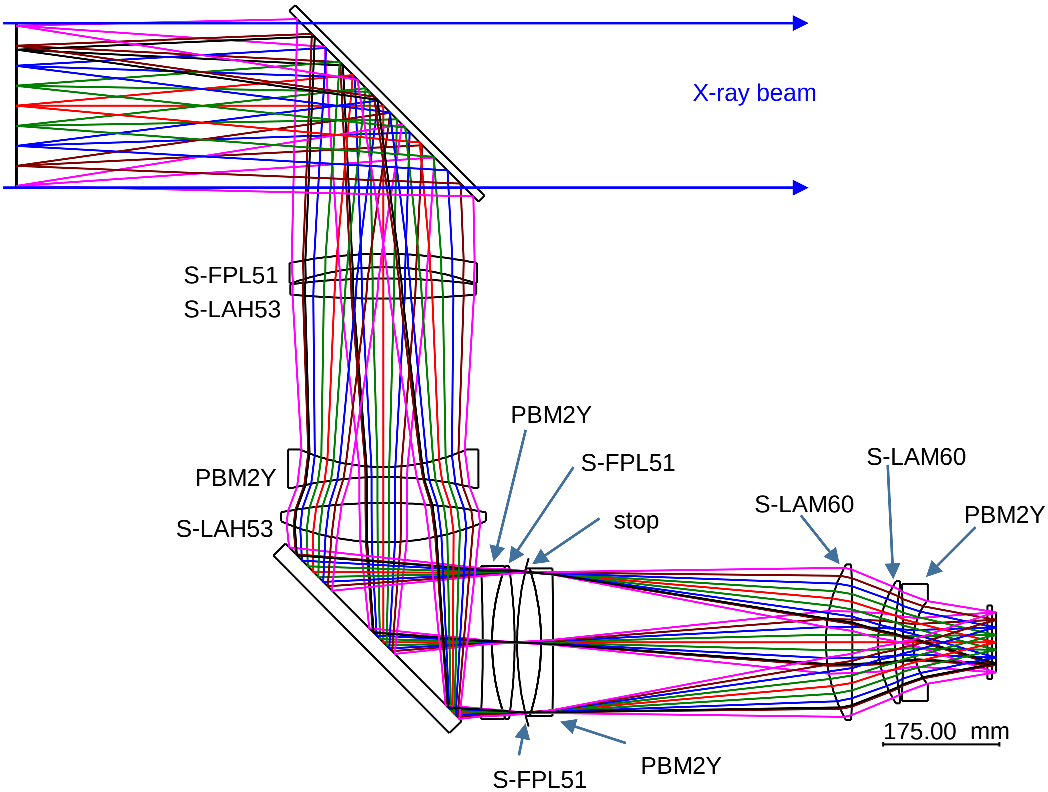

Fig 8. This optical design was achieved by fixing the glasses indicated in Figure 4 first. Then, the distortion algorithm was applied.

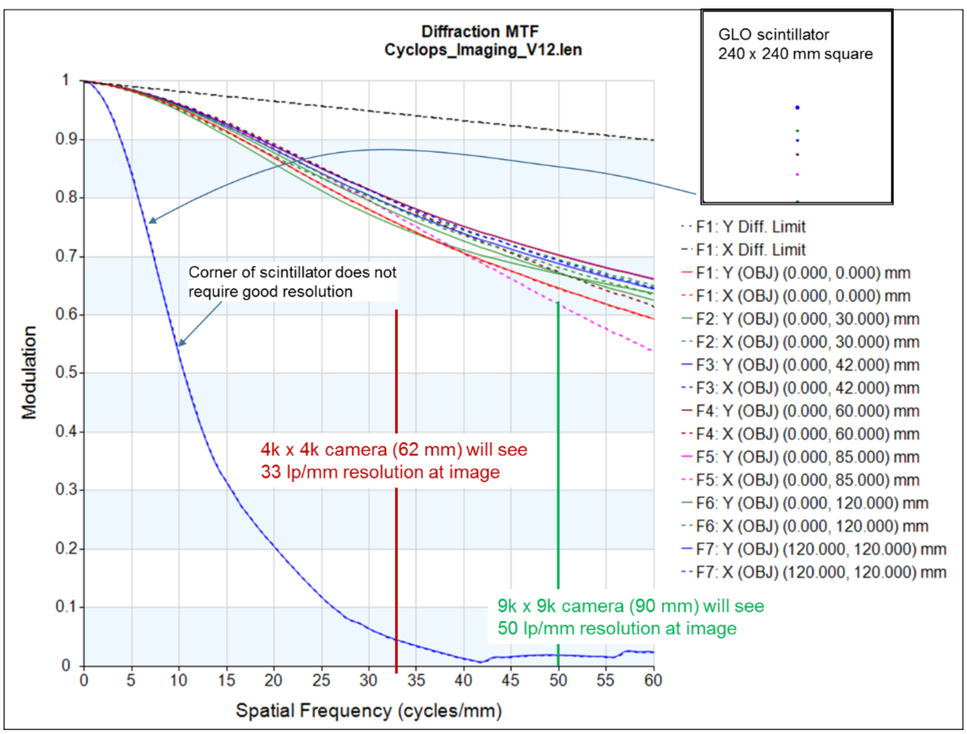

Fig. 9. We have achieved better resolution than the last design shown in Figure 5. The blue curve is the outermost corner of the scintillator.

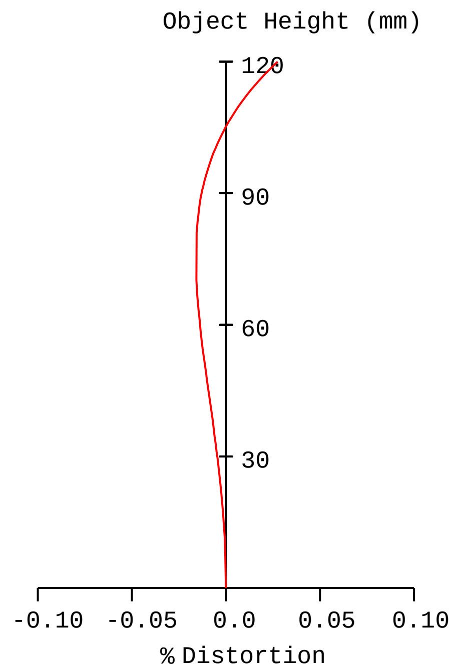

Fig. 10. We have again achieved the distortion requirement which is 0.02%. However, this result is not quite as good as the previous design.

3. Discussion

To achieve distortion-free systems, localized surface figure tolerances need careful considerations [5,6]. Field points that have small footprints on a surface need much tighter surface figure tolerances to achieve low distortions. The amount of distortion does not have to vary linearly across the image plane. Thus, the image could have different values of distortion at localized image positions. The first four lens elements and the last three lens elements require tighter surface figure tolerances. Slope errors on these optical surfaces lead to ray deviation at the image plane.

Our acceptance criteria to measure system performance is still developing. Additionally, we envision quality checks of the MTF and distortion to take place on a periodic time scale. We are working on a lithographic plate design that will have lines of different thicknesses for MTF measurements as well as small holes spread across the plate surface to measure distortion at localized positions in the image.

Table 1. Optical system specifications

Scintillator size	240 × 240 mm
9000 × 9000 image size	90 × 90 mm
Scintillator type	GLO(Eu)
Number of pixels at image	9000 × 9000 mm
Pixel size at image	0.010 mm
Nyquist frequency	50 cycles/mm
Magnification	0.375
Lens EFL	570 mm
Max. chief ray at scintillator	5.11
Max chief ray at camera	4.875
Percent distortion at edge	0.01%
Percent distortion at corner	0.003%
Langth of folded lens elements	1520 mm
Max. optical element diameter	291 mm
f/#	2.08

Acknowledgments
This manuscript has been authored by National Security Technologies, LLC, under Contract No. DE AC52-06NA25946 with the U.S. Department of Energy, National Nuclear Security Administration, U.S. DOE Office of Defense Programs. The United States Government retains and the publisher, by accepting the article for publication, acknowledges that the United States Government retains a non-exclusive, paid-up, irrevocable, world-wide license to publish or reproduce the published form of this manuscript, or allow others to do so, for United States Government purposes. The U.S. Department of Energy will provide public access to these results of federally sponsored research in accordance with the DOE Public Access Plan (http://energy.gov/downloads/doe-public-access-plan). DOE/NV/25946--3293.

References

[1] R. M. Malone, S. A. Baker, K. K. Brown, A. H. Curtis, D. L. Esquibel, D. K. Frayer, B. C. Frogget, M. R. Furlanetto, J. R. Garten, T. J. Haines, R. A. Howe, J. A. Huerta, M. I. Kaufman, N. S. P. King, S. S. Lutz, K. D. McGillivray, and A. S. Smith, "Design and assembly of a telecentric zoom lens for the Cygnus x-ray source," Proc. SPIE **8488**, 84880B (2012).

[2] R. M. Malone, S. A. Baker, K. K. Brown, J. J. Castaneda, A. H. Curtis, J. Danielson, D. W. Droemer, D. L. Esquibel, T. J. Haines, J. S. Hollabaugh, R. A. Howe, J. A. Huerta, M. I. Kaufman, N. S. P. King, S. S. Lutz, K. D. McGillivray, A. S. Smith, B. M. Stokes, and A. Tibbitts, "Alignment and testing of a telecentric zoom lens used for the Cygnus x-ray source," Proc. SPIE **8844**, 88440A (2013).

[3] N. J. Cherepy, Z. M. Seeley, S. A. Payne, E. L. Swanberg, P. R. Beck, D. J. Schneberk, G. Stone, R. Perry, B. M. Wihl, S. E. Fisher, S. L. Hunter, P. A. Thelin, R. R. Thompson, N. M. Harvery, T. Stefanik, and J. Kindem, "Transparent ceramic scintillators for gamma spectroscopy and MeV imaging," Proc. SPIE **9593**, 95930P (2015).

[4] M. I. Kaufman, D. K. Frayer, R. M. Malone, A. Corredor, and B. B. Light, "Design guidelines for predicting stress in cemented doublets undergoing temperature change," International Optical Design Conference 2017 (this conference).

[5] M. C. Sanson, C. T. Tienvieri, and S. Van Kerkhove, "Localized slope errors and their impact on image performance requirements," Proc. SPIE **6342**, 634223 (2006).

[6] Rogers, J. R., "Slope sensitivities for optical surfaces," Proc. SPIE **9582**, 958206 (2015).