MWIR CONTINUOUS ZOOM WITH LARGE ZOOM RANGE

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ABSTRACT

Multiple fields of view are achieved by two methods. The system can have optical groups that flip in and out to change the field of view, and/or optical groups that move axially to change the field of view. For flip in systems, the fields of view are discreet and they may have greatly different fields of view. A zoom system can have a continuous change in the field of view, but is often limited in the field of view range that can be achieved. Corning Incorporated has developed a thermal imaging zoom system with greater than 30X zoom range. With a solid fundamental design and appropriate selection of moving group focal lengths, the zoom system provides continuous changes in the field of view from the narrow field of view to the wide field of view. Corning accomplished this result in a short package with just two moving groups. The system is for the MWIR band.

Keywords: Optical design, Zoom lens, Infrared Lens, MWIR, Diffractive optics

1. INTRODUCTION

It is often desirable, or necessary, for optical systems to have multiple fields of view. In addition, specifications may restrict the size and weight of the system in which the designs will be used. There are several ways for a system to have multiple fields of view. A design could use multiple cameras and optical paths, but such a design typically would increase the weight and size of the system. A system can use a single camera as well as a single aperture. In these configurations the field of view would be changed with moving optics. The system could have optics that flip in and out, move axially, or both. It has been found that the field of view between different configurations should not be greater than 4X[1]. At least 4 different configurations would be necessary for a large overall change in magnification (i.e. 30X). Here we will examine creating a large continuous zoom range system.

For years, designers have developed infrared systems for the LWIR. In the last several years, designers have built systems that work in the MWIR. The advantages of the MWIR are an increase in resolution and in some atmospheric conditions, and an increase in ID range[2,3].

Advances in optical design and fabrication continue to create more complex optical systems. Discussed here are some of the challenges of designing a MWIR continuous zoom with a large magnification range.

2. DESIGN CONSIDERATIONS

This design involved 3 main components that required consideration at the start of the design process; (1) the system was designed for the 3-5um spectral band, (2) it is a zoom system, and (3) the design has a significant thermal range during operation. It is a good practice to have an understanding of prior art. It is not necessary, and arguably not wise, to use an existing design as your starting point, but an understanding of existing designs and the reasons for their different characteristics is important.

The design of a MWIR lens system will limit the available materials. The correction of the chromatic aberrations will require several different materials of varying dispersions. The thermal range makes using CaF_2 unwise, but there are several other materials available[4]. The system was designed to work with 2nd generation cameras, so Narcissus also must be examined[5,6].

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A 2nd generation camera with cold stop requires the common relay before the camera to keep the diameter of the front objective element controlled. Many systems contain optics that flip or rotate in between the front objective and relay to create multiple fields of view[1,7,8,9]. A zoom system was created in this design space. With the proper 1st order selection this space has enough room for the elements to move and create a large zoom range.

There is much in the literature about designing zoom systems and the many pitfalls that can occur[10]. The type of zoom system chosen for this design is the traditional two moving group zoom system. There are several reasons for this choice. Only two moving groups are necessary for a system to change magnification while maintaining a fixed focus. In the absence of a third constraint a third moving group was not used. The additional moving group typically would add significant weight. The complexity of the additional group in terms of 1st order optimization as well as mechanical design places a heavy burden that requires good justification. With proper 1st order selection, the required zoom range was found to be achievable with two moving groups.

The 1st order analysis of the zoom lens indicated that a very large zoom range was not likely achievable without the well published discontinuity which typically occurs when the two zoom elements produce a 1X magnification[11]. This solution was not optimal, but could be made transparent to the end user. Both the size and performance degradation of the discontinuity can be controlled. Because this system is controlled electronically, a small discontinuity would be acceptable[10,12]. With optimization, the discontinuity could be eliminated by proper root selection and 1st order parameter selection. This topic is covered by ChunKan[13].

With the basic layout determined, the 1st order layout of the zoom was optimized with perfect lenses. We determined the front focal length, the zoom magnification range, and the magnification of the relay group. Then the components were designed based upon the 1st order layout. This process allowed for a starting design that had some minimal wavefront performance as a system before the final optimization was done for the complete system.

3. ACTUAL DESIGN

The zoom system presented here is based upon the specification presented in table 1. The design form can be migrated to other camera specifications by decreasing the F/# and image plane size. The design also accommodates mirror placements for different packaging requirements.

Table 1. Characteristics of the optical design presented

Characteristics	Typical Value
Zoom Range	> 30X
Focal Length Range	15.25 - 456mm
Spectrum	3 - 5 μm
F/#	4.5
Image Plane Diagonal	12.3mm
Front Element Diameter	120mm
Total Track	355mm
Distortion	< 0.5%
Transmission	> 70%
Number of Aspheres	8
Number of Diffractives	1

The zoom range listed here is 30X, but the limitation is not mechanical. The focus and MTF performance is maintained for wider fields of view, but the Narcissus and illumination uniformity will begin to dominate.

The design contains 1 diffractive and 8 aspheric surfaces. The front objective is kept as just a singlet for Narcissus and weight considerations. The zoom groups take on the common -/+ focal lengths to produce a large zoom range. This configuration does a good job of controlling the pupil and preventing the objective from becoming too large. The relay operates close to unity.

Because the optics are diamond turned, the use of aspheres is not cost prohibitive. For this type of zoom system, they are vital to the performance given the small overall length[14].

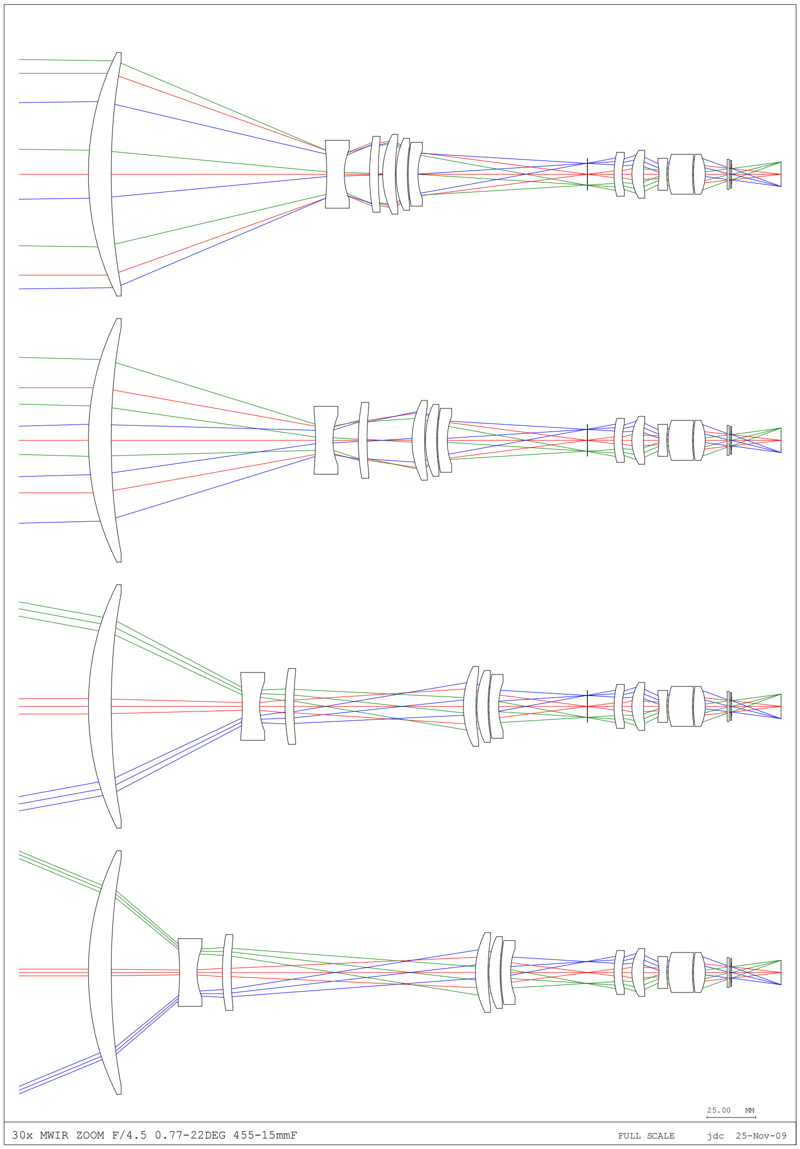

Figure 1. The layout shows the smooth path of the zoom groups throughout the range. It also shows that the WFOV is not limited by any glass to glass collisions.

3.1 Performance

The MTF performance of this system is nearly diffraction limited throughout the entire zoom range. Through optimal use of different materials and a single diffractive surface, we controlled the chromatic errors. The plots in figures 2, 3, and 4 show the designed MTF at three fields of view. There is a slight departure from the diffraction limit at the corner of the field of view.

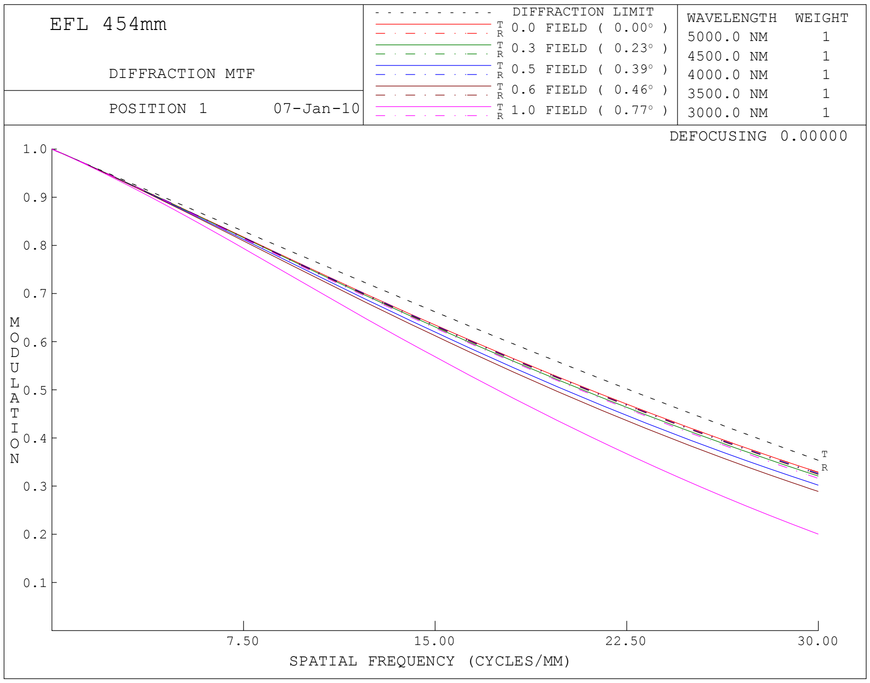

Figure 2. The NFOV MTF is shown out to Nyquist of the designed camera. It is close to the diffraction limit for the entire field.

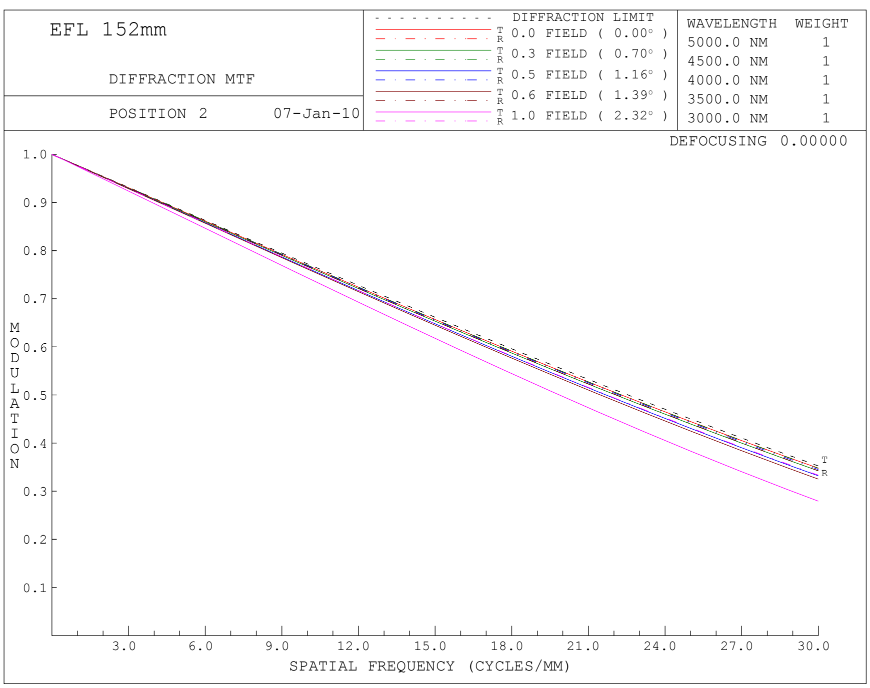

Figure 3. A typical MFOV MTF is shown out to Nyquist of the designed camera. Through most of the zoom range, the system is diffraction limited.

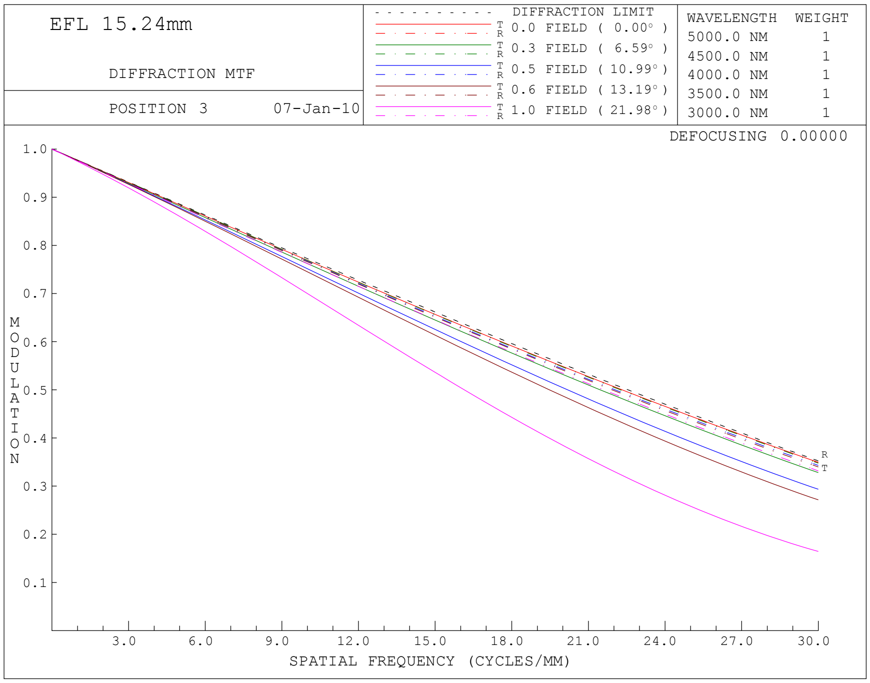

Figure 4. The WFOV MTF is shown out to Nyquist of the designed camera. There is some drop in performance only at the very corner of the FOV.

Furthermore, the distortion of this zoom system is under 0.5% for the entire 30X range. Figure 5 shows the distortion across the full focal length range.

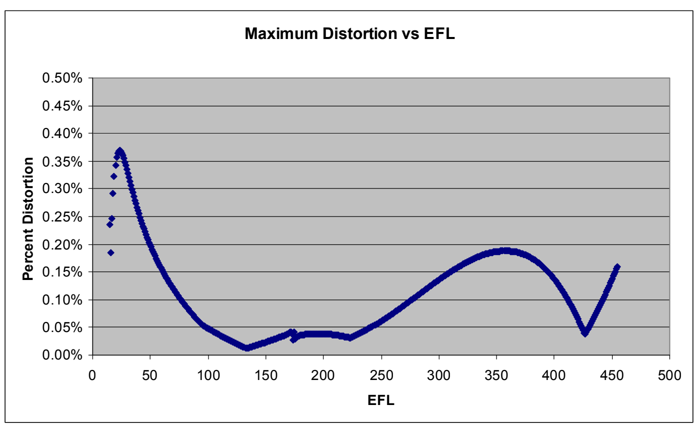

Figure 5. The distortion of the system is low through the entire zoom range.

3.2 Zoom group motions

Shown in figure 6 is the continuous motion of the zoom groups. Extra precautions were taken around the case where the magnification of the zoom section equals 1X. The focal length of the system and the movement of the lens groups are smooth and continuous. The number of zoom configurations selected during optimization was based upon evaluating the preliminary design over very small focal length changes over the zoom range. The evaluation revealed several focal lengths to include in the optimization, while keeping the number of configurations to a minimum for speed considerations.

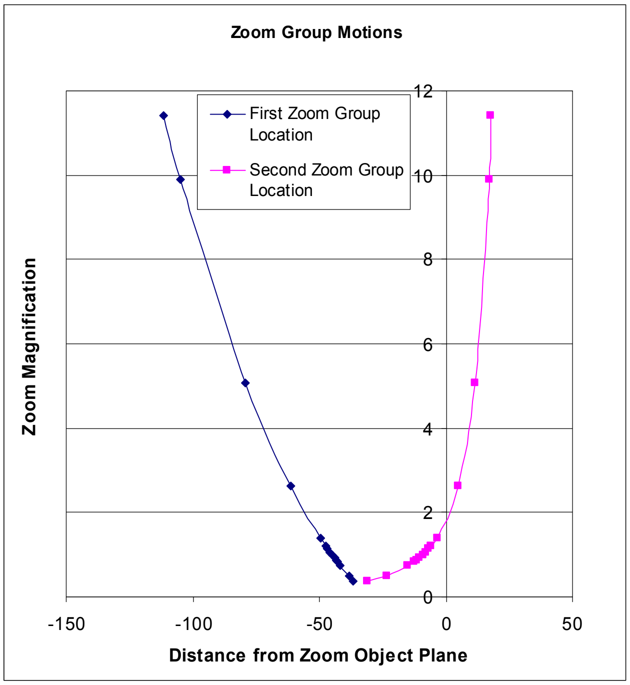

Figure 6. The zoom paths of the system are smooth. We used extra care in the region where the zoom magnification was 1X.

Figure 7 demonstrates the ability of the zoom groups to "switch roots" around the 1X. Figure 7 depicts the close look at the zoom group motions near the 1X magnification. Two solutions allow the groups to have a given magnification. Although the focal length of the system is the same with these alternate positions, the performance of the lens quickly deteriorates as you move away from the 1X zoom position. This deterioration results from the alternate positions not being used during the optimization.

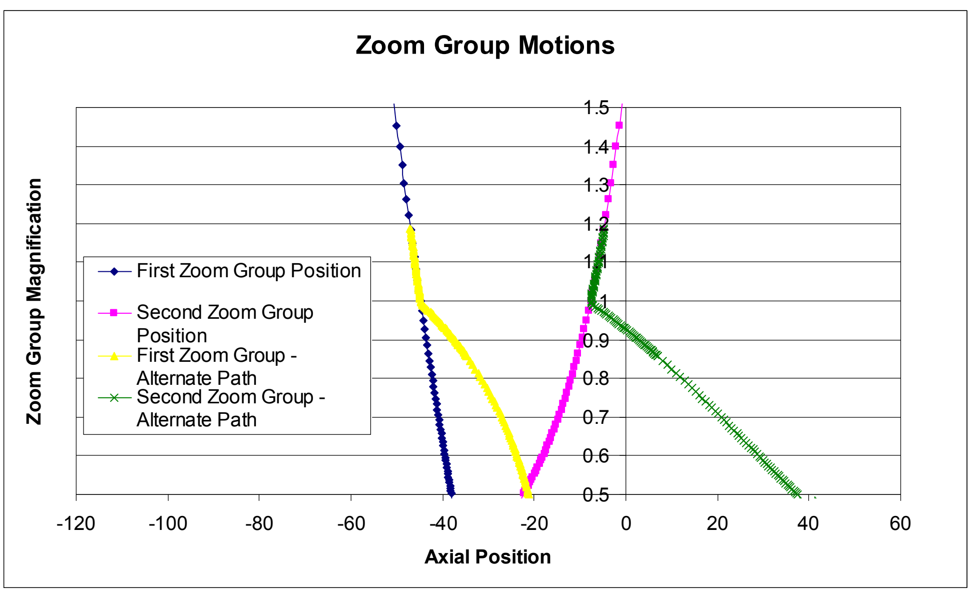

Figure 7. The "alternative" zoom paths deviate from the smooth designed path at the 1X zoom magnification location.

Figures 8 and 9 present various system aberrations through the entire zoom range. Although the focal length and physical motions of the optics are smooth, there is a very small discontinuity in the performance. As shown, this discontinuity would not be noticeable by the detector. No measureable change in contrast occurs about the focal length when the zoom groups have a magnification of 1X.

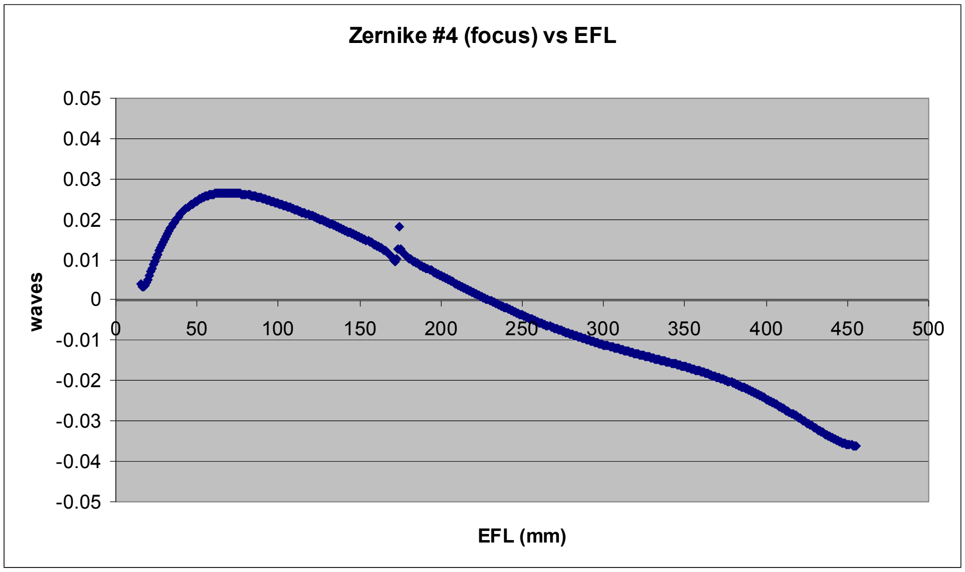

Figure 8. The small discontinuity of focus can be seen from this plot. The amount of defocus is negligible.

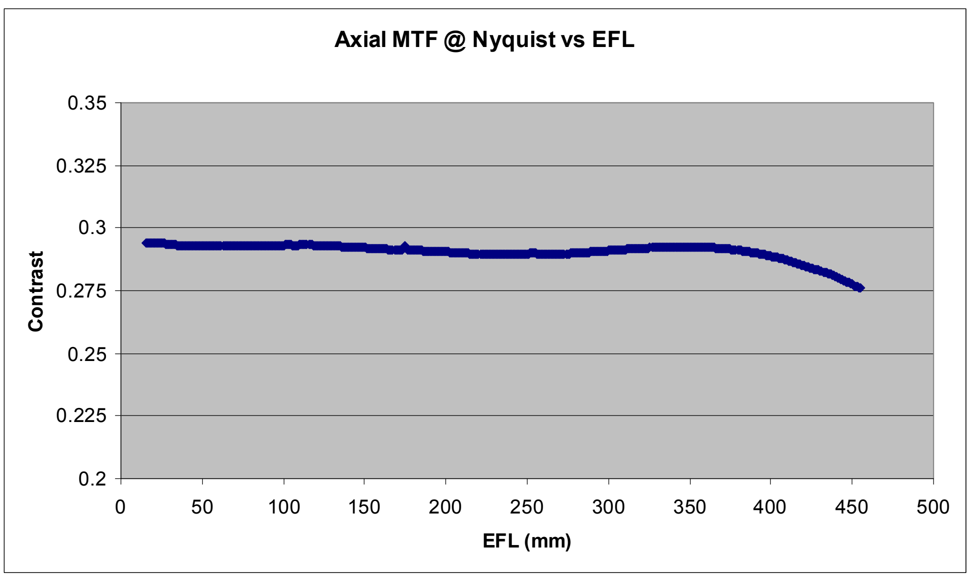

Figure 9. The small discontinuity of focus is hardly visible in this plot showing the axial MTF value at Nyquist across the zoom range.

3.3 Sensitivities

The angles of incidence were controlled during the design to prevent problems for coating as well as to help control sensitivities. The most sensitive airspaces were found in the 2nd zoom group at the NFOV and the final air-spaced doublet of the relay. These airspaces will be controlled very precisely during the build process.

By keeping the powers of the zoom groups as large as possible we were able to keep the sensitivity of the groups low from the beginning. We discovered the zoom groups could handle a +/-50μm decentration tolerance and still have no impact to MTF or distortion. Boresight was the parameter that was most effected, but it can be compensated.

3.4 Narcissus

This system is configured for cameras that contain staring arrays and cold stops. Since the elements are moving the effects of narcissus change must be examined[5,15]. The first order narcissus contributing quantities of YNI and I/I_b as well as single bounce ghost reflections from the cold stop back to the FPA were evaluated and selected surfaces were targeted during optimization. The zoom range will require the camera to be capable of calibrating the effects of the narcissus for several regions through the zoom range. As mentioned prior, the decision was made to keep the front objective group as a single element. Using LightTools[16] non sequential ray tracing and ray path filtering, the main contributors to narcissus can be identified. Figures 10 and 11 show the primary surfaces on the objective element that contribute to narcissus at the WFOV. Figure 12 reviews the results of the initial narcissus analysis for all surfaces. To reduce the effect of the front surfaces, the coatings will be geared toward minimizing the low angle of incidence reflections in the regions used at the WFOV.

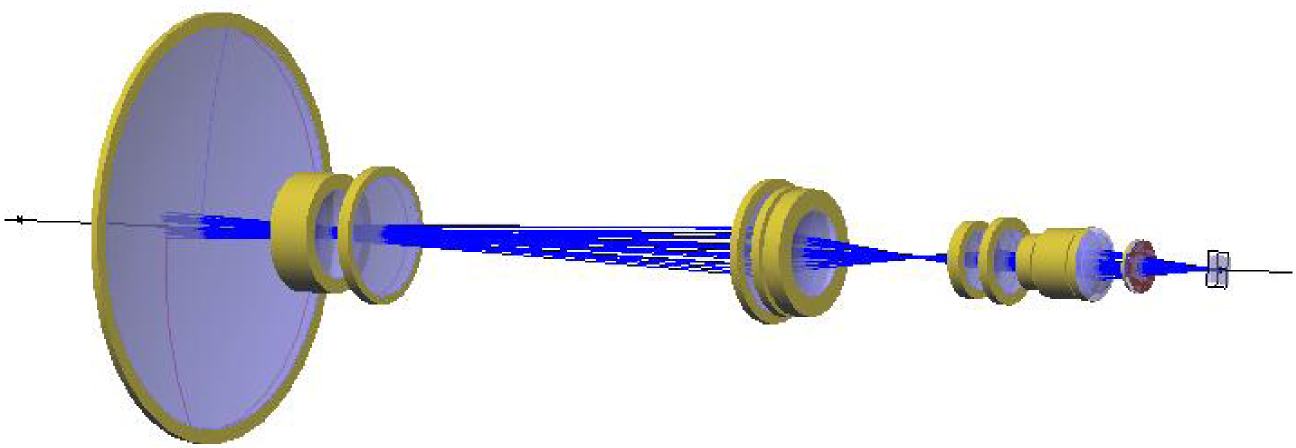

Figure 10. The front element is the largest contributor to narcissus. The single bounce ghost is shown here.

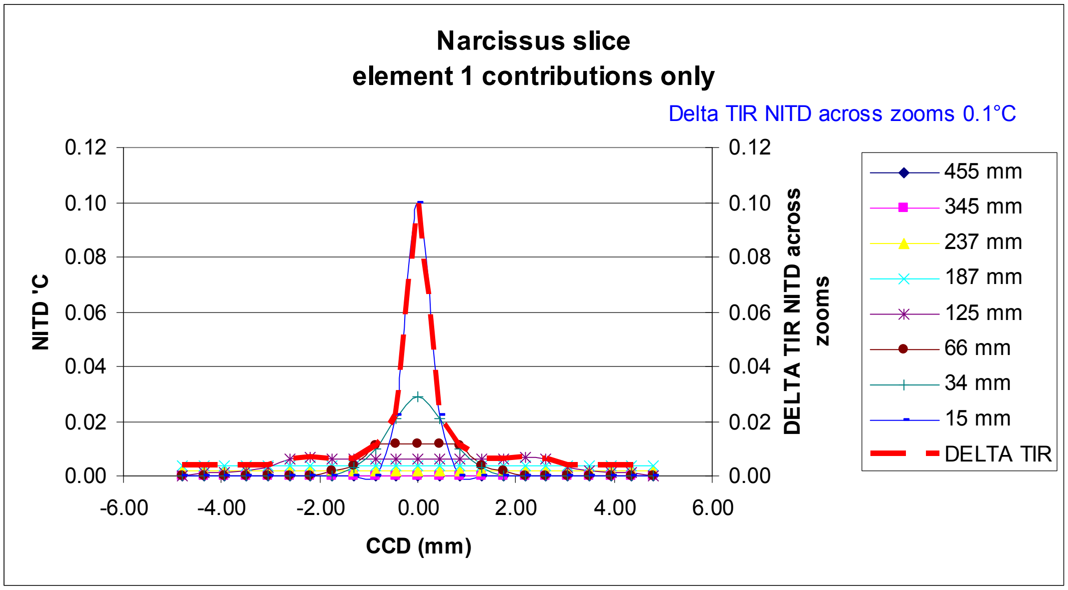

Figure 11. The Narcissus effects of the front element are shown here. Element 1 contributes 1/3 of the total narcissus difference across the zoom range.

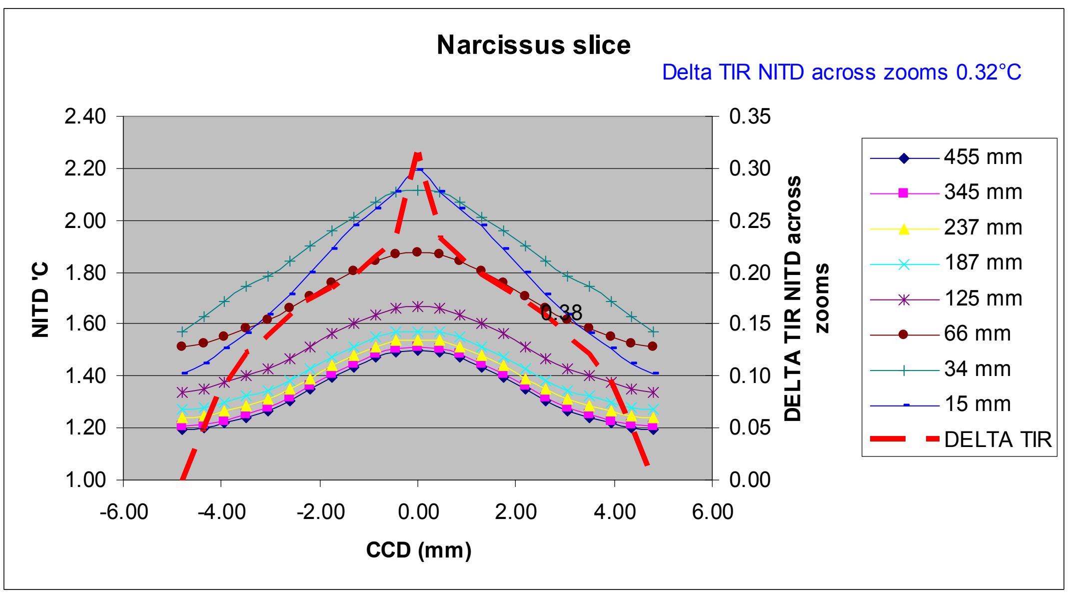

Figure 12. This graph illustrates the Narcissus affects at different focal lengths. Multiple calibrations can be taken to reduce the effect.

3.5 Thermal

The thermal range of the zoom system was found to be the most demanding. Designers have relied on many methods to handle focus for thermal variations[11]. With Germanium in each of the zoom groups, a fair amount of focal length variation occurs with temperature change. Because the design uses motors and slides, as opposed to a cam, the movement of each zoom group could be independently positioned. The compensation for thermal changes is handled by adjusting the zoom groups with a lookup table.

The image performance was fully recoverable through compensation across a very broad thermal range. Figure 13 depicts the NFOV and WFOV at temperature extremes of -40°C and +60°C.

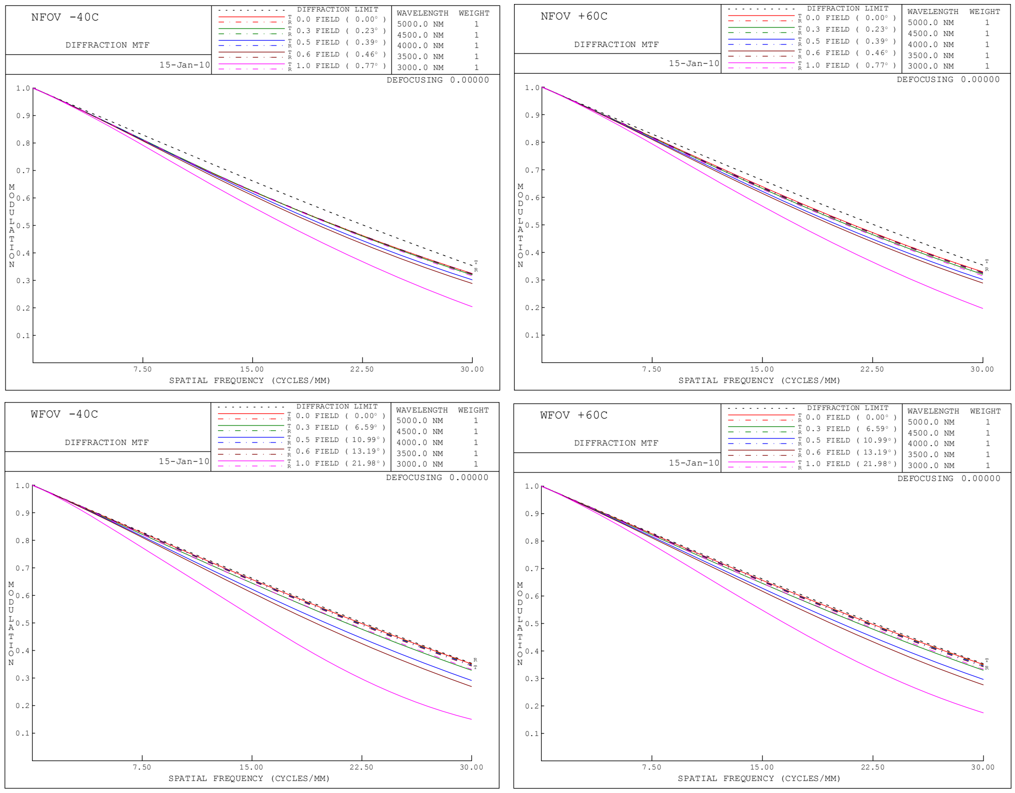

Figure 13. The MTF plots of the NFOV and WFOV at both temperature extremes show no loss of performance after application of active compensation.

3.7 Image Simulations

In figure 14 & 15 the results of CODE V[17] image simulation are displayed[18]. The nearly diffraction limited performance at both ends of the 30X zoom range are shown. The distortion at either focal length is not noticeable.

Figure 14. The object file is shown on the left and the results of the IMS are on the right. The performance is from the WFOV of the zoom system. The pixel size of the camera has been convolved with the performance of the lens.

Figure 15. The object file is shown on the left and the results of the IMS for the NFOV are on the right. The pictures here demonstrate the 30X magnification of the WFOV images. The people are located in front of the building of figure 14.

3.8 Close Focus Range

The system is also designed for close focus. There is no performance loss at the WFOV up to 25 meters without any compensation. The NFOV required compensation by moving the second zoom group. With the compensation, a close focus of 25 meters shows no loss in performance. The MTF plots are shown in figure 16.

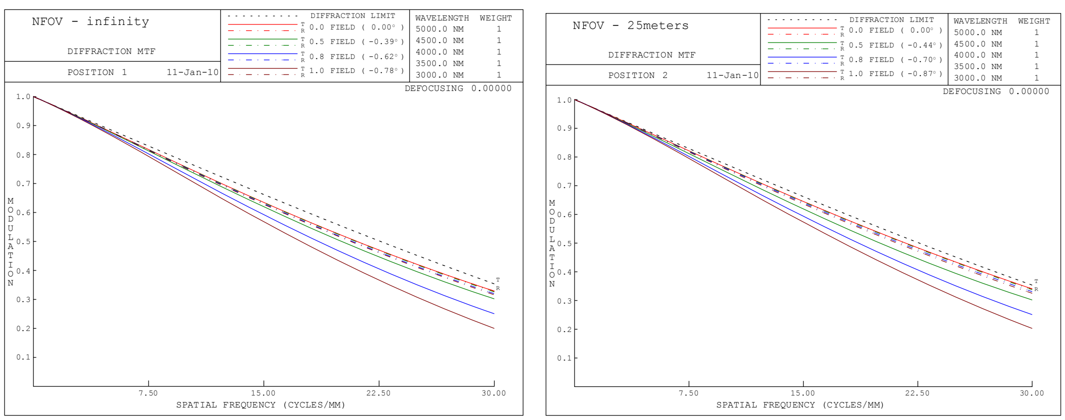

Figure 16. The nominal MTF curves for an object at infinity are shown on the left, with the corresponding MTF for an object at 25 meters is on the right.

4. SUMMARY

By understanding the many different aspects of an optical system, a straightforward path can be used to develop a design. The MWIR zoom lens presented exceeds the zoom range of current known MWIR systems. We accomplished this result with a small total track length. With knowledge of the problems that can occur with zoom designs, MWIR designs, and systems with large thermal range, the starting point of the design along with optimization controls employed during the development minimized problems.

REFERENCES

[1] Akram, Muhammad, "Design of a multiple-field-of-view optical system for 3- to 5-μm infrared focal-plane arrays," Opt. Eng. 42(6), 1704-1714 (2003)

[2] Richardson, Phil and Driggers, Ronald G. , "Atmospheric turbulence effects on 3rd generation FLIR performance," Proc. SPIE 6207, 1-11 (2006).

[3] Richardson, Phil and Miller Brian , "Third Generation FLIR Simulation at NVESD," Proc. SPIE 6543, 1-11 (2007).

[4] Vizgaitis, Jay, " Selecting Infrared Optical," University of Arizona, Optics 52, December 14, 2006.
[5] Scherr, Lawrence M., Orlando, Harold J., Hall, James T., and Godfrey, Thomas B. "Narcissus Considerations in Optical Designs for Infrared Staring Arrays," Proc. SPIE 2864, 442-451 (1996).
[6] Feng-Yun, He, Ji-Cheng, Cui, Shu-Long, Feng, and Xin, Zhang, "Narcissus Analysis For Cooled Staring IR System," China Proc. of SPIE Vol. 6722, 1-7 (2007).
[7] Yong, Li, Changcheng, Yang, and Shenghui, Li, "Design of Infrared Zoom System with Rotating Lens Group", Proc. of SPIE Vol. 6834, 68343Y (2007).
[8] Akram, Muhammad, "Design of a Dual Field-of-View Optical System for Infra-Red, Focal-Plane Arrays", Proc. SPIE Vol. 4767, 13-23 (2002).
[9] Patent US4486069(A)
[10] Neil, Iain A., "Optimization glitches in zoom lens design," SPIE Vol. 3129, pg 158-180 (1997).
[11] Ford, Eric, "Active Temperature Compensation of an Infrared Zoom Lens," SPIEVoI. 3129, 138-143 (1997).
[12] Fischer, Robert and U.Kampe Thomas, "Actively Controlled 5:1 Afocal Zoom Attachment, for Common Module FLIR," SPIE Vol. 1690, 137-152 (1992).
[13] ChunKan, Tao, "Design of zoom system by the varifocal differential equation," Applied Optics VoI. 31, 2265-2273 (1992).
[14] Betensky, Ellis, "The role of aspherics in zoom lens design", SPIE Vol. 1354, 656-662 (1990).
[15] Feng-Yun, He, Ji-Cheng, Cui, Shu-Long, Feng, and Xin, Zhang, "Narcissus Analysis For Cooled Staring IR System," Proc. of SPIE Vol. 6722, 1-7 (2007).
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