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DESIGN AND MANUFACTURE OF THE WORLD'S LARGEST REFRACTIVE ZOOM SYSTEM

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ABSTRACT

The world's largest refractive zoom optical system was designed and manufactured by Eidolon Corporation. Four afocal zoom systems were built as part of a mobile, laser radar tracking system. Each zoom had an aperture of 12.5" and a magnification range of 1x - 10x

Keywords: Zoom, optical tracking, laser radar, laser tracking.

1. INTRODUCTION

Beginning January 1990, and until April 1993, Eidolon Corporation was under contract to the Environmental Research Institute of Michigan, to design and build a Near-IR Zoom optical tracking system. The purpose of the system was to acquire and precisely track a cooperative target, namely the B2 Stealth Bomber. The Mobile High Resolution Tracking System (MHRTS) makes precise measurements of the target's position relative to the tracking site, and relay those measurements to Mission Control.

The MHRTS system consists of (4) separate optical channels, all mounted within a structural truss assembly. Each of the (4) channels features a 10x magnification all-refractive afocal zoom telescope with a clear aperture of 12.50" diameter. These are the largest refractive zoom optical systems ever to be manufactured in the United States.

The purpose of two of the optical channels is to transmit laser energy collected from laser diode emitters. The Track Transmit channel uses (4) 1-watt Laser Diode Modules (LDM) that are multiplexed into a 10x Afocal Zoom Telescope. The Search Transmitter channel uses (4) 3-watt LDM's that are multiplexed and then scanned into another 10x Afocal Zoom Telescope. Figure 1, a side-view CAD drawing of the MHRTS assembly, shows the Search and Track Transmit channels. Figure 2 is a drawing of a 1 watt LDM.

The two other channels in the MHRTS system are the receivers, appropriately named the Search Receiver and the Track Receiver. The Track Receiver utilizes another 10x Afocal Zoom Telescope and imaging optics to focus the backscattered laser light onto a quad cell detector. The Search Receiver features a 25-element detector that is imaged and then scanned in elevation by a galvanometer type scanner and re-imaged into the entrance pupil of another 10x Afocal Zoom Telescope.

Each of the 4 channels is mounted on its own Eidolon custom-made all-aluminum honeycomb optical bench. The top and bottom surfaces of the optical benches are made of 6061-T6 aluminum with the central core made of aluminum honeycomb laminated with epoxy. All mounting locations are reinforced by internal aluminum stanchions that span the entire thickness of the table. This insures that there will be no local surface deformations to the optical bench so that the required optical alignment will be maintained. The truss assembly is manufactured of 1/8" wall thickness 2" x 3" aluminum tubing TIG welded together.

The all-aluminum truss assembly was designed using the finite element analysis computer program ANSYS to insure that the 1250 lbs of payload are properly supported and that the system pointing accuracy of 25 micro-radians is maintained in azimuth and elevation for an angular slew rate of 0.625 rad/sec and an angular acceleration of 0.625 rad/sec^2.

Eidolon Corporation was responsible for all of the engineering design and manufacture of MHRTS. The entire design project for Eidolon encompassed the system conceptual and detailed design, optical design, mechanical design, and structural design of the support truss and optical tables. Eidolon also performed the complete manufacture of the MHRTS system, which included the optical fabrication, the machining of opto-mechanical components and sub-assemblies, the machining and welding of the truss support assembly, system assembly, alignment, testing as well as integration of MHRTS with the pedestal.

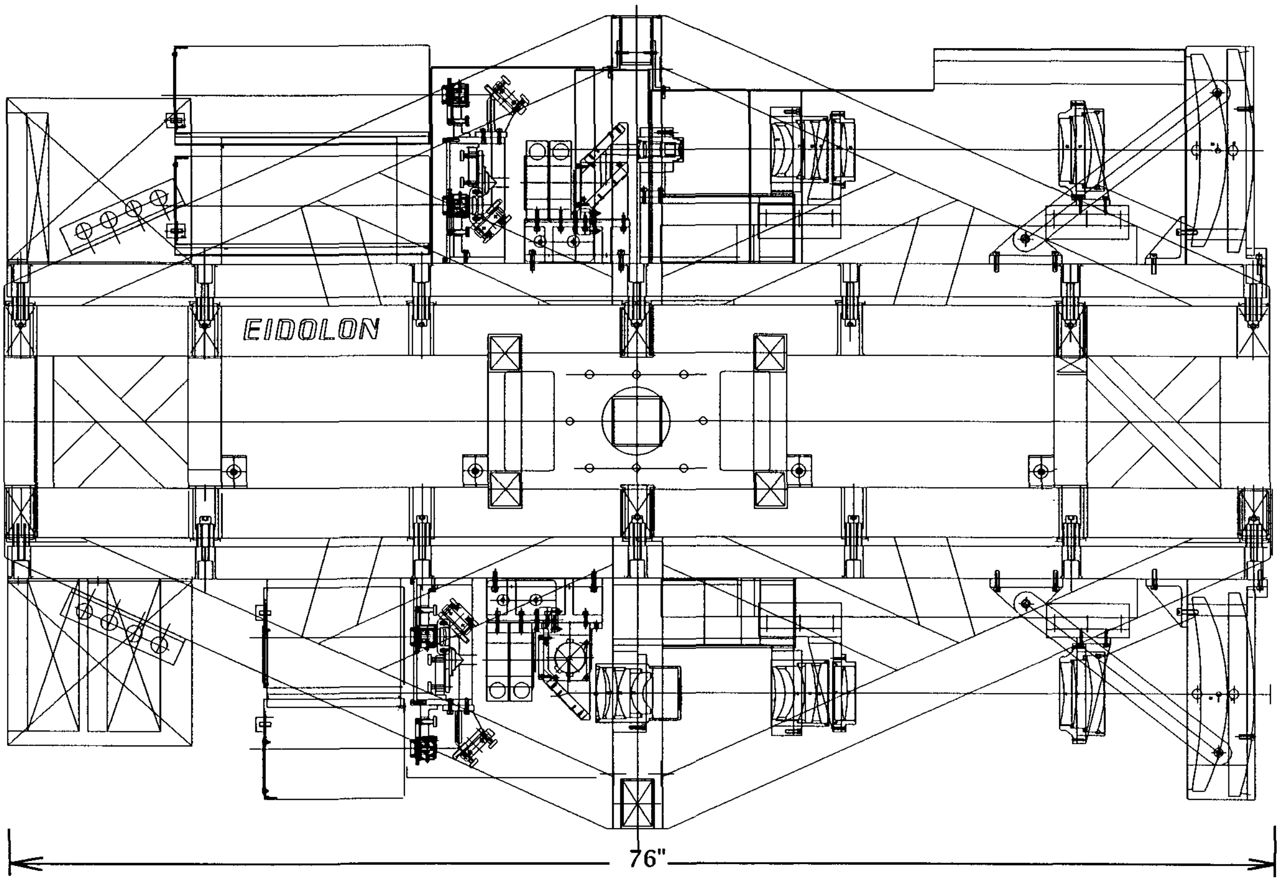

Figure 1 - Mobile High Resolution Tracking System

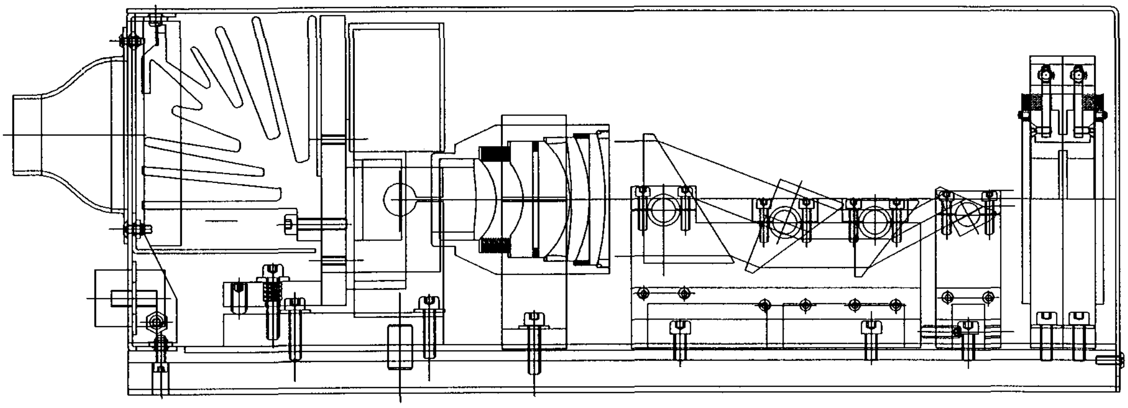

Figure 2 - Laser Diode Module for Track Transmitter

2. SYSTEM CONCEPT

2.a Mobile Tracking System

The function of the mobile tracking system is to provide the capability to acquire and precisely optically track a cooperative target in the field. The target would typically carry an array of corner cube reflectors in order to maximize the laser return. Figure 3 depicts the entire mobile tracking system. The Eidolon laser optical tracker is mounted to an Az-El pedestal, housed inside the dome on the trailer.

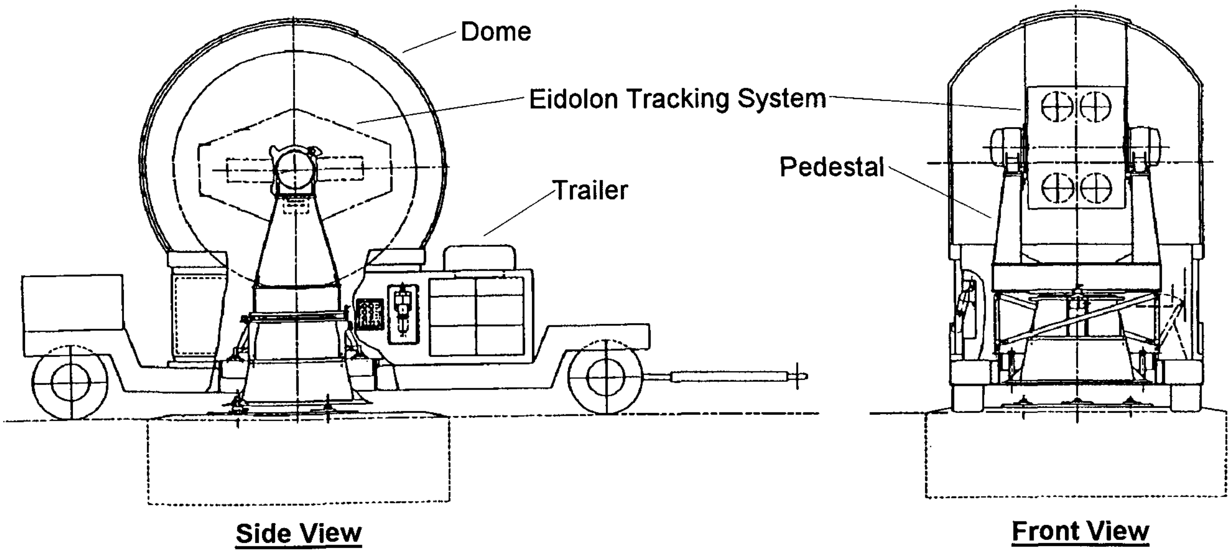

Figure 3 - Mobile Optical Tracking System

2.b Tracking System Operational Performance Requirements

The operational performance requirements of the Mobile Tracking System were developed to insure a very high probability of tracking range/position accuracy. They are:

- Target Range 1 to 20 km, in clear weather (0.35 dB/km visibility)
- Continuous tracking of target over entire range
- Detection and tracking within 0.02 seconds
- Maximum angular velocity of target 0.625 radians/second
- Operating temperature range -30° to +45° C.
- Azimuth and Elevation accuracy to 75 microradians
- Range resolution to 0.01 meters

From the above operational performance requirements flowed the specific performance requirements and design considerations for the Eidolon Laser Optical Tracking system. Since continuous tracking capability over a broad target range of from 1 to 20 km was required, it was determined that a refractive zoom optical system with a 1x - 10x magnification would be used for each of the 4 transmitter/receiver channels. A refractive configuration was selected instead of a reflective optical system since it was critical that there be no obscuration of the exiting laser beam in the transmitters. From the S/N calculations (source to detector) it was determined that the aperture of each of the zoom optical systems be 300 mm (12.0").

The large operational temperature range required that thermal considerations be given to every aspect of the optical/mechanical system. First, it was decided that the truss structure, (4) optical tables, the zoom lens cells, and virtually every metal part larger than a cubic inch be made of 6061-T651 aluminum alloy to insure uniform thermal growth. Next, an active, closed loop thermal compensation scheme for the zoom telescopes was developed using (8) temperature sensors per zoom, and temperature dependent lookup tables for the zoom motion controllers. Finally, the optics of the (4) 1-watt Track Laser Diode Modules (LDM's) and the (4) 3-watt Search LDM's were designed to be thermally compensated passively by selecting the optical and mechanical material with the appropriate coefficients of thermal expansion. Twentieth-wave RMS beam quality was maintained for the LDMs over the entire operational temperature range using passive compensation.

The pointing accuracy and slew rate requirements of the Mobile Tracking System placed an exceedingly difficult burden on the Eidolon engineers, particularly with the structural design of the truss. To insure that the total Mobile Tracking System would have an Azimuth and Elevation pointing accuracy of 75 micro-radians, it was required that the deflection error budget for the Eidolon Laser Tracker be 25 micro-radians. This requirement had to be met dynamically at 50% of the maximum slew rate from 0° to 60° in elevation angle. In addition, two other design constraints were placed on the truss mechanical design: weight was to be minimized and the fundamental vibration mode frequency was to be maximized.

2.c The Eidolon Laser Optical Tracking System

As indicated previously, Eidolon Corporation was responsible for the design and manufacture of the laser optical tracking system as shown in Figure 4.

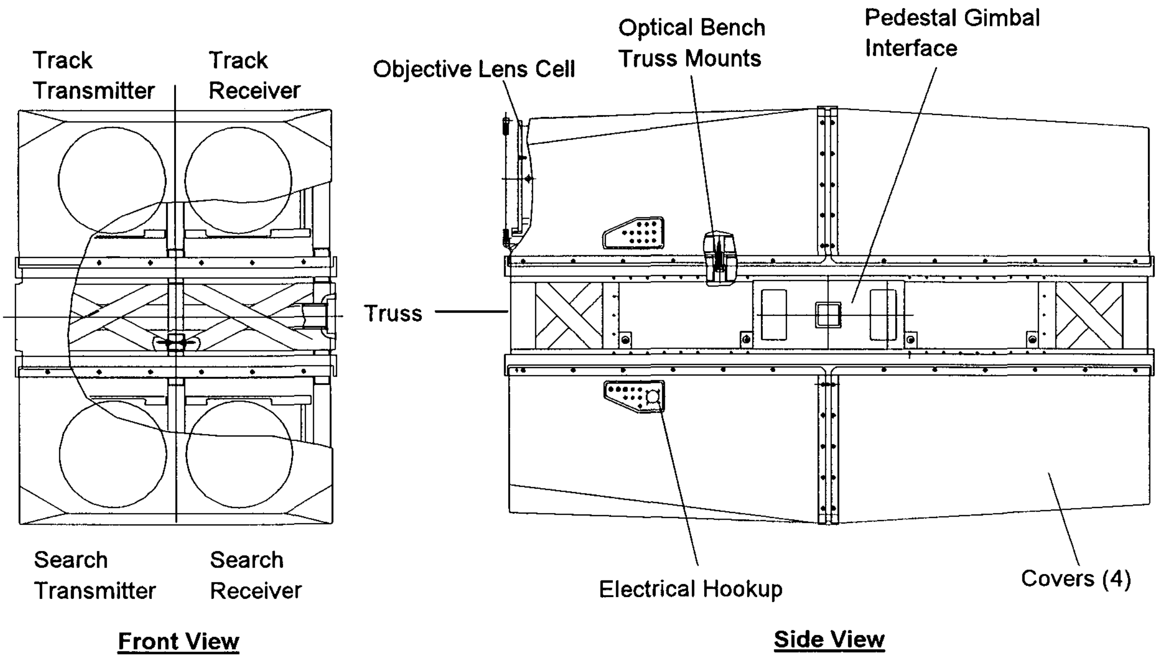

Figure 4 - The Eidolon Laser Optical Tracking System

The Eidolon Laser Optical Tracking System comprises the following 7 sub-assemblies:

- Afocal Zoom telescopes (4)
- Laser Diode Modules, (4) 1-watt (Track Transmitter) and (4) 3-watt (Search Transmitter)
- LDM Multiplex Assemblies (Search and Track Transmitters)
- Detector Modules for Search and Track Receivers
- Optical tables for all (4) channels
- Payload Truss
- Retro-Reflector Corner Cube Array (attached to the cooperative target)

The purpose of this paper is to present a detailed description of the optical design, development and manufacture of the Afocal Zoom Telescopes. A complete description of the entire Mobile Tracking System will presented in a future paper.

3. ZOOM TELESCOPES

3.a Optical Requirements

The optical requirements for the Search and Track Afocal Zoom systems were developed by Eidolon in conjunction with our customer as part of the conceptual design phase of this development project. As a result of our conceptual design efforts, it was determined that the optimum configuration for the zoom systems be afocal and that their overall magnification range be 10x. A summary of the important design requirements for the Search and Track Afocal Zoom systems are listed in the following table:

Optical Design Requirements of the Search Afocal Zoom systems (2)

- Afocal, 1x - 10x magnification range
- 300 mm dia. entrance pupil at 10x
- External optical stop
- 2.5 mrad FFOV at 10x (Az)
- 25 mrad FFOV at 10x (El)
- Achromatic, 805 to 815 NM
- Distortion, < 0.5%
- Maximum length = 40.0"
- Thermally compensated
- Residual design error < 0.05 waves RMS

Optical Design Requirements of the Track Afocal Zoom systems (2), (same as Search except:)

- 2x - 20x magnification range achieved by re-design of eyepiece

3.b Optical Design Summary

Figure 5 is a computer-generated plot from Code V of the Eidolon Afocal Zoom at 1x, 2x, 4.5x and 10x magnifications, shown with the Search eyepiece. We achieved the specified requirements after 1 man-year of optimization with Code V running on a Digital MicroVax II computer during 1990-91. We designed this system at 7 zoom positions, for 2 wavelengths (800 and 820 NM), and 3 field positions. Due to the large optimization matrix, each optimization cycle took approximately 45 minutes. Today, in 1995, using the same software and a 486-66 MHz or Pentium based computer, the optimization would be about 25 to 35 times faster.

As a result of the intensive optical design optimization, we were able to meet all of the design goals. Our efforts resulted in an optical design for the 10x Afocal Zoom that featured a total of 15 lens elements.

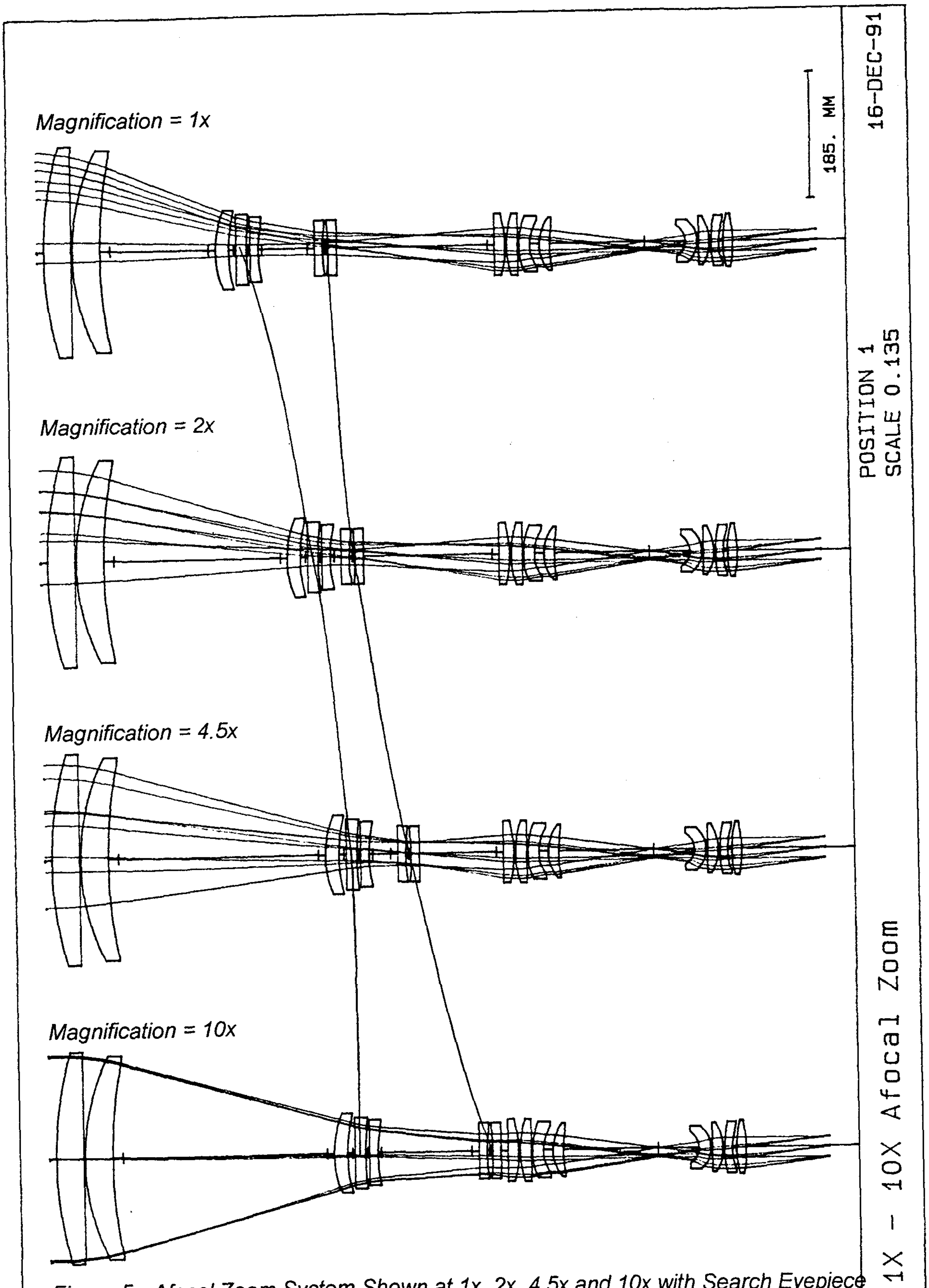

Figure 5 - Afocal Zoom System Shown at 1x, 2x, 4.5x and 10x with Search Eyepiece

The following table is a summary of the final optical design that was manufactured.

- 2-element BK7 Objective, (+)
- 3-element Variator, (net -)
- 2-element Compensator (-)
- 4-element Relay (+)
- Intermediate Image Plane
- 4-element Eyepiece
- Re-imaged Optical Stop, External Exit Pupil
- Compensator and Variator travel overlap
- Residual Design Error = 0.041 waves RMS
- Distortion = 0.25%
- Overall Length = 40.20"

Figure 6 shows the Afocal Zoom system at 10x magnification with the various optical groups identified.

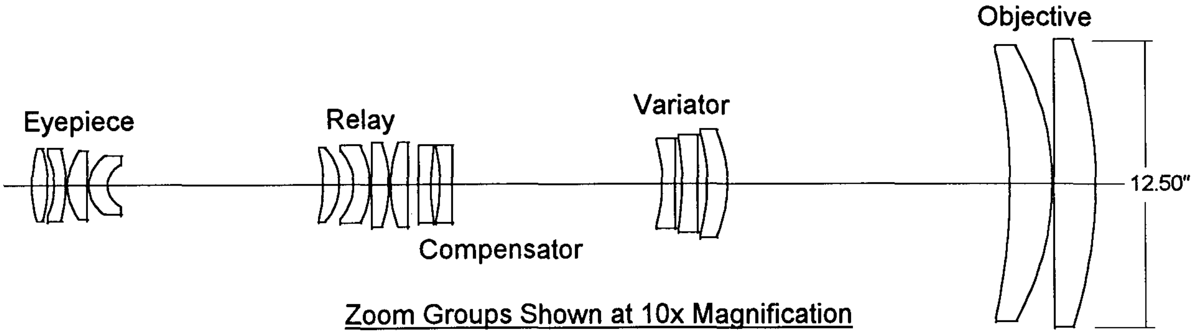

Figure 6 - Afocal Zoom Shown at 10x Magnification with Search Eyepiece

The most difficult constraint to control in the optical design optimization of the Afocal Zoom was length. It was required that the overall length of the Afocal Zoom be less than 1 meter. Since it was also required that the aperture of the objective lens be 12.0", this forced the F/number of the objective to be F/2. With an F/2 objective, correction of the high order spherical aberration introduced at 10x magnification became essential.

The principal design feature that was implemented to minimize the overall length of the Afocal Zoom system was to allow the two moving zoom groups paths, namely the variator and compensator, to overlap. At first, our mechanical engineers were in a quandary as to how this could be implemented. Then we came up with the idea of having both the variator and compensator shuttles ride on a common pair of crossed roller bearings, and driving each shuttle with its own separate lead screw/stepper motor. Figure 7 is a photograph of one of the four custom, double-shuttle slides manufactured to Eidolon design specifications by New England Affiliated Technologies, Inc.

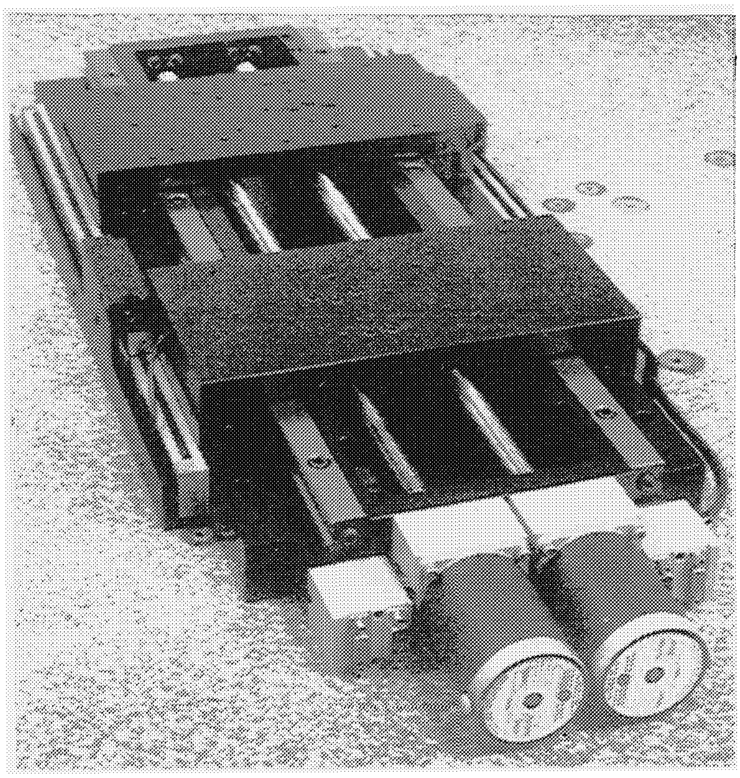

Figure 7 - Double Shuttle Slide Motion System for Zoom Variator and Compensator

3.c Mechanical Design of the Objective Lens Cells

The objective lens cells were designed to support the 2-element objective lenses over the temperature range of -30° to +45° C. Lens elements 1 and 2 have a diameter of 12.500" and 11.750" respectively. Due to the extremely tight boresight alignment tolerance, any lateral movement of the lens elements with temperature could not be tolerated. Selecting the lens cell material with the same coefficient of thermal expansion as the BK7 lens elements was not practical primarily because of the weight consideration. Instead, we chose to manufacture the lens cells from 6061-T6 aluminum and passively compensate for the non-uniform thermal growth of the objective lenses and the cell by utilizing a differential thermal expansion technique. This technique involved the use of (8) Delrin plastic plugs symmetrically positioned around the periphery of each lens element. The plugs are held captive by blind holes bored on the inside of the lens cell. The length of each set of Delrin plugs was calculated to insure that the differential expansion of the *glass-plastic-aluminum* system was zero over the required temperature range. An aluminum spacer separates the two objective lenses. The objective lenses are held axially in the cell by a 12.250" ID by .187" O-ring compressed by an aluminum flange retainer ring bolted to the lens cell body. The assembled objective lenses and cell were thermally tested over the entire temperature range and no lateral or axial movement in the lens elements was detected. Figure 8 depicts the mechanical design.

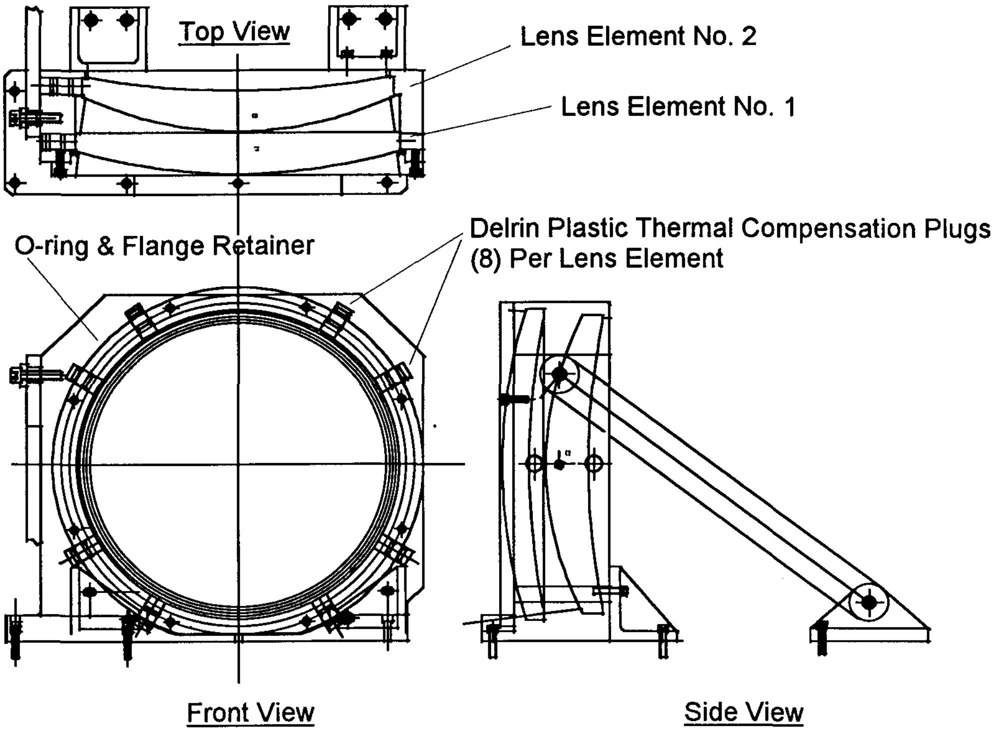

Figure 8 - Mechanical Design of the 12.50" Diameter, 2-Element Lens Cell

3.d Meeting the Boresight Error Specification

One of the most critical requirements placed on the Eidolon Afocal Zoom systems was the boresight wander error as a function of the zoom magnification. In a zoom optical system there are usually two or more moving groups of optical elements that have the potential for introducing boresight wander error. Typically, errors in the opto-mechanical alignment, mechanical play in the motion control system, or optical manufacturing error in the lens elements, in any of the moving zoom groups can cause boresight wander error.

The tolerance for boresight wander error for the Afocal Zoom systems was 10 μradians, to be maintained over the entire magnification range of from 1x to 10x. We were informed by various consultants representing our customer and other technical experts that this was an exceedingly difficult if not impossible requirement to meet. Because of the importance of meeting the boresight wander tolerance and the perceived high risk of doing so, it was an issue at every design review and technical meeting.

Our approach in meeting this exceedingly tight tolerance was based around one simple, elegant idea, namely to make the stationary pair of crossed roller bearings on the double shuttle slide assembly, be the opto-mechanical reference around which all of the optical elements in the zoom systems were to be aligned. We first aligned the optics in the variator and compensator zoom groups to the double shuttle slide crossed roller bearings. Since the variator and compensator have weak net negative optical power in comparison to their relatively large required travel during zooming, the sensitivity to boresight error as a result of misalignment is small for both groups. Next, using the conventional alignment procedure with an alignment telescope and a set of inside micrometers, we aligned the objective lens assembly, then the relay optics, and finally the eyepiece, to the crossed roller bearing reference. Figure 9 depicts the opto-mechanical assembly of the zoom system. Using this procedure we were able to align each of the Afocal Zoom systems in a few hours time.

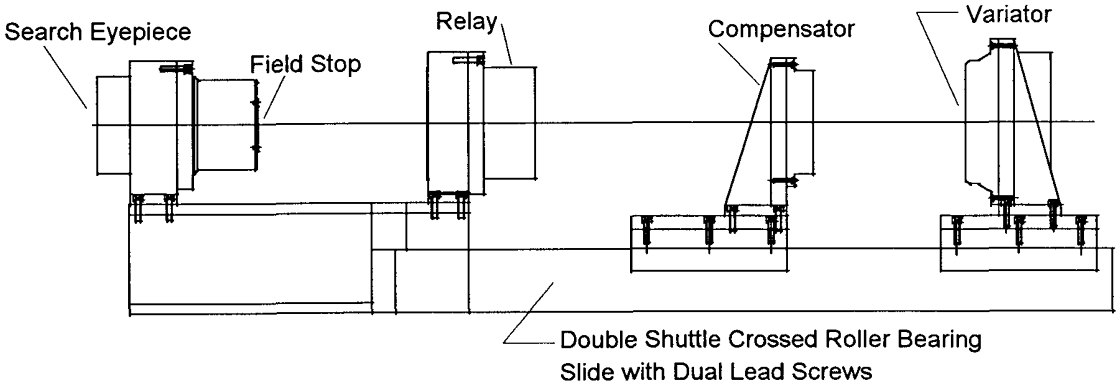

Figure 9 - Variator and Compensator Shuttles Share a Set of Crossed Roller Bearings

3.e Measuring Boresight Wander

The boresight wander versus zoom magnification was determined by measuring the Line Spread Function (LSF) at a number of positions over the entire 10x zoom magnification range. Using the Eidolon FastMTF measurement software in conjunction with our boresight wander test station hardware, we were able to acquire and display in real time, the LSF of each of the Afocal Zoom systems.

The boresight wander test procedure as developed by Eidolon is described as follows. A full aperture (12.50") collimator was placed in front of the Afocal Zoom under test. A 25 μ dia. pinhole illuminated with an 830 NM laser diode was placed at the focal point of the collimator. The resultant 12.50" diameter collimated beam was then collected by the Afocal Zoom. A calibrated, diffraction-limited lens of known EFL was placed at the opposite end of the Afocal Zoom to collect the light exiting the eyepiece. The Point Spread Function (PSF) of this lens was then relayed optically to a high-resolution CCD array camera. The Eidolon FastMTF software processed the PSF image and produced the LSF information. FastMTF performs two onedimensional FFTs on LSFs derived from the PSF[1]. The LSF is computed by adding up the pixel intensity data along either rows and columns over the entire CCD camera detector area.

Since the LSF is the integrated intensity of the PSF as a function of position, by comparing the shift of the peak of the LSF with the peak of the LSF at a different zoom position, and using the appropriate scale factor (related to the EFL's of the collimator and relay optics) we can determine the boresight wander versus zoom magnification. Figure 10 is the computer-generated output of the LSF from FastMTF for the Search Receiver Afocal Zoom system. From this plot we were able to calculate that the boresight wander was less than 3.0 μradians from 1x to 10x magnification. This compares very favorably with the required 10.0 μradian tolerance. The boresight wander versus zoom magnification of the three other Afocal Zoom systems were measured and similar results were achieved.

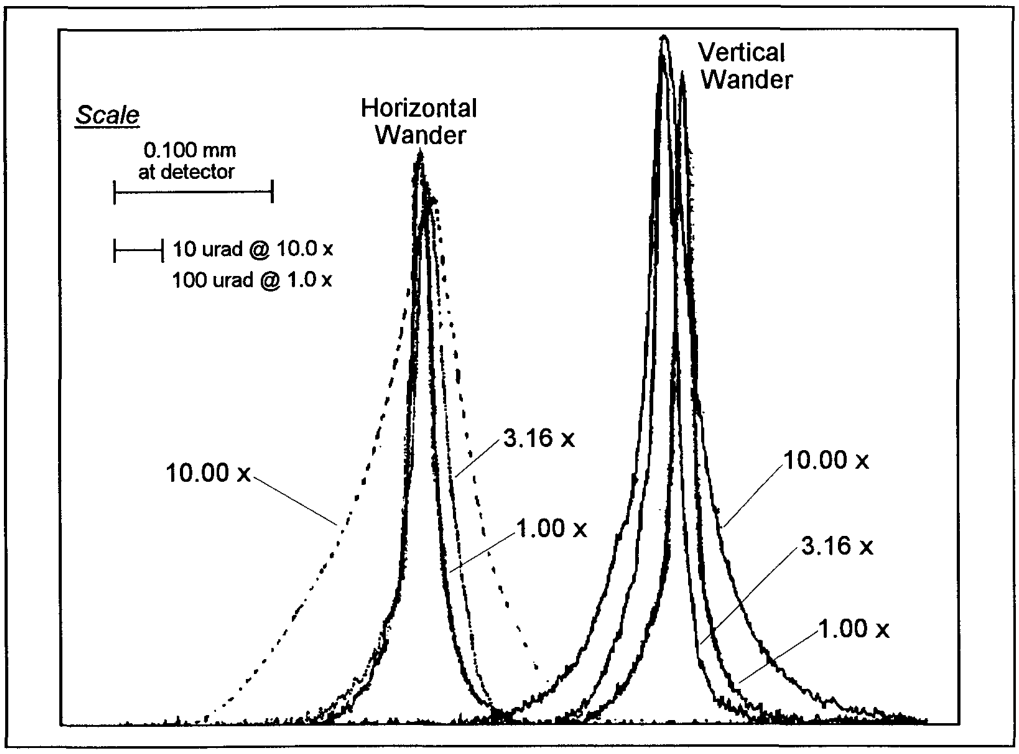

Figure 10 - Boresight Wander Error versus Zoom Magnification as Determined by Measuring the Horizontal and Vertical Line Spread Function

3.f Optical Performance of the Manufactured Zoom Telescopes

The optical performance of the Eidolon Afocal Zoom systems was determined to meet all the requirements as specified in the statement of work. Each Afocal Zoom was tested for optical transmission, wavefront error (interferometrically), MTF, and boresight wander, over the entire zoom magnification range. These tests were repeated at numerous points throughout the required operating temperature range. In every instance, the specification was met. Figure 11 is a photograph of one of the completed Eidolon Afocal Zoom systems.

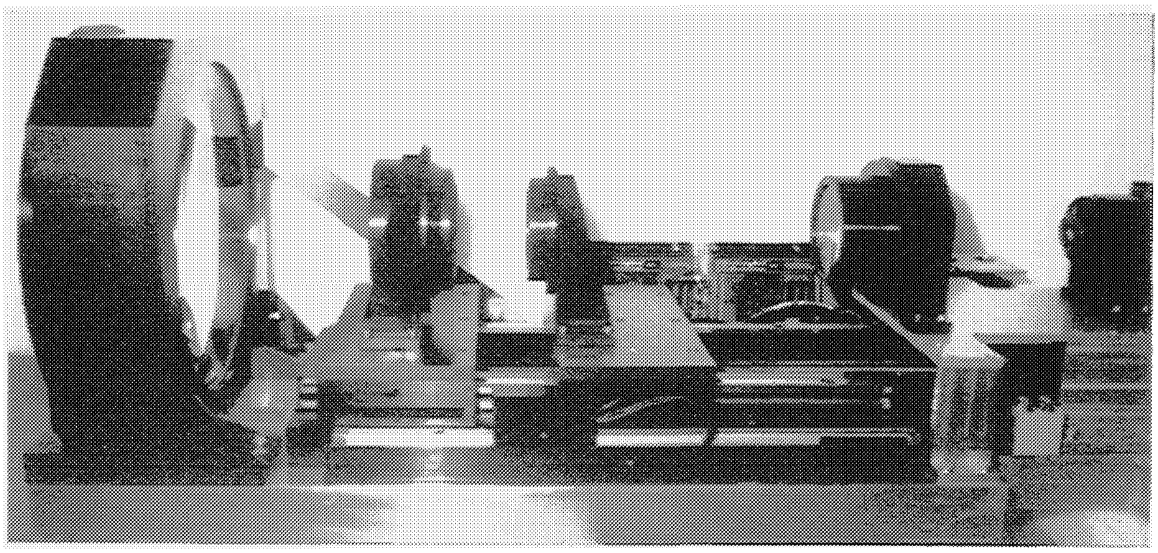

Figure 11 - An Eidolon Afocal Zoom System, 12½" Aperture, 10x Magnification

4. CONCLUSION

The design and manufacture of the world's largest refractive zoom system was completed by a relatively small group of highly skilled and self-motivated individuals from Eidolon Corporation. The technical achievement encompassed the advancement of zoom system design not only in size but in the areas of optical performance, boresight retention, thermal compensation, and mechanical rigidity/stability as well.

5. ACKNOWLEDGMENT

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6. REFERENCES

1. Doherty, V. J., and Chapnik, P. D., "Precision evaluation of lens systems using a nodal slide/MTF optical bench", *SPIE* Vol. 1531, Advanced Optical Manufacturing and Testing II, pp. 103-118, (1991).