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Modular design/assembly/alignment approach to an infrared (IR) scanning system

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Abstract

The infrared scanning optical system to be considered is an 8 to 11.5 μm dual-field-of-view configuration. With production, the ultimate goal of such a system--a cost-effective, production-compatible design--assembly and alignment methodology is imperative. The optical design approach of previous configurations was modified so as to provide a modular system whereby preassembled, aligned, and tested modules can be "bolted together" and, with a minimum of adjustments, yield an acceptable level of performance.

This paper discusses many of the optomechanical design tradeoffs which lead to a final modular system design. Module assembly, alignment, and test methodology are discussed.

Introduction

The optical design form representative of several advanced development IR scanning systems is shown in Figure 1. It consists of:

1) A zinc sulfide dome

2) A telephoto group of two elements, "E1" and "E2"

3) A fold mirror (which, in some systems, also provides interlace)

4) A collimating lens group consisting of a common lens "C" which is always in place, a narrow- field-of-view lens "N", and two wide-field-of-view lenses "W1" and "W2". The field of view is selected by placing either "N" or "W1" and "W2" in the beam. These elements are in a rotating housing so that the field of view can be rapidly changed.

5) An internally faceted scan mirror (see Figure 2) which rotates at about 3000 rpm so as to provide an appropriate raster scan. The scan mirror also serves as the free gyro of the system.

6) A focusing lens which focuses the collimated radiation onto the detector.

Although a number of systems were successfully produced using the above basic design philosophy, it was more often than not found that the lens seat for element "C" was not machined within tolerance, and time-consuming differential shimming was usually required so as to properly center this as well as the other lens elements. In order to provide a more production-compatible system, a modular optical design lending itself to a production environment was mandatory. This paper discusses the following:

- The tradeoffs and ultimate generation of a more "modularized" optical design for production compatibility

- The fabrication, assembly, and alignment tolerances and methodology of implementation

- Test plans and methods for providing rapid semiquantitative go/no-go production-compatible tests of the optical modules

Optical design considerations

In order to best present the optical design tradeoffs, consider first the packaging requirements in Figure 3. Because of the system gimbal requirements and scan methodology, a "double-dogleg" fold is required, with virtually all mechanical constraints frozen. Figure 4 shows simplified design representations of the narrow and wide fields of view. The most important specification from which a first-order design can be configured is the magnification which is defined here as the ratio of the chief ray angle in scan mirror space (θ_s) to the chief ray angle in object space (θ_o). This is essentially the same as the ratio of the entrance pupil diameter (D_o) to the collimated beam diameter at the scan mirror (D_s). The chief ray must also be imaged onto the scan mirror as shown. In the wide field, θ_s must be the same as in the narrow field, but the object space chief ray angle must be twice that of the narrow ($2\theta_o$) for a 2X system.

The above is a very brief summary of some of the first-order design considerations, and is intented to help review the relative design complexity necessary to meet the requirements.

Figure 4 intentionally shows the minimum number of optical elements with which the first-order requirements can be met. Proceeding to a real optical design, it is found:

1) Element "N" of Figure 4a must be split into two elements as shown in Figure 5 in order to eliminate the astigmatism of elements "E1" and "E2" without introducing unacceptable lateral color. This is similarly the case for element "W2". In addition, splitting this element reduces pupil aberration (i. e., spherical aberration of the chief rays from the entrance pupil to the exit pupil at the scan mirror). Pupil aberration would cause undesirable cosmetic effects on the display.

2) Element "F" optimally is an achromatic doublet so as to eliminate the primary axial color introduced almost exclusively by the zinc sulfide dome.

The optical design approaches used in advanced development units have utilized a common element ("C") present in both fields of view as noted earlier. One of the major methods of modularizing the optics is to place all lenses between the fold and scan mirrors into a single rotating housing.

A design form was optimized with the aid of the CODE V optical design program utilizing two narrow-field collimating elements ("N1" and "N2"). The penalties of not splitting element "W2" are increased lateral color and astigmatism as predicted, but the degradation at the format corners in the wide field was considered acceptable. Both narrow and wide field modes were optimized simultaneously with three scan angles modeled for each mode using the "ZOOM" subroutine of CODE V. The system is thus a "six-position ZOOM system" represented by a single net error function relative to performance. Mechanical constraints are easy to control in each mode. Optimization of complex systems of this form has been found to be extremely well handled by CODE V.

The final optical design is shown in Figure 6. The design is nearly diffraction limited over the entire format in the narrow field of view, and over nearly the entire format in the wide field of view.

It is worth noting that the following two alternate wide field design forms were generated which both produce an excellent level of performance across the entire format:

1) Three wide-field elements (i. e., splitting element "W2")

2) A single aspheric surface was allowed on one side of element "W2". An excellent level of performance was obtained, and the element is fully retrofittable into the present housing. This solution thus represents a viable upgrade should improved wide-field performance at the format extremes be desired. Existing single-point diamond-turning technology is fully capable of producing the asphere in production.

Aperture sizing considerations

A modulation of warm radiation would occur, for example, with classical vignetting where the relatively warm cell or housing is infringing into the entrance pupil at extreme scan positions. This will create undesirable cosmetic effects in the form of bright areas on the display. In order to keep this "scan noise" within acceptable levels (under 1 to 2 percent of the pupil area), extremely detailed ray trace analyses are required to assure that the apertures are sufficiently large and that no mechanical structure infringes into the pupil. The nonrotational symmetry of the system, as well as the square format and tight packaging requirements, requires a full three-dimensional computer model whereby the system is precisely modeled, even down to the individual scan mirror facet geometry.

Figure 7a shows a typical ray trace analysis whereby all limiting radiation bundles occurring in the plane of the figure over the format and detector array extent are shown. An enlarged view of the collimating lens area is shown in Figure 7b, where it can be seen how these elements are actually slabbed or truncated because of the packaging constraints.

Fabrication, assembly, and alignment tolerances - and method of module implementation

In order to assure that the system will meet its performance requirements as well as to provide tolerances for optical and mechanical components, a complete tolerance analysis is imperative. To this end, the "TOR" tolerancing subrouting of CODE V was used to evaluate the effects of the error budgeted tolerances including all element radii, power fit to test plates, surface irregularities, refractive indices, thicknesses, wedges, tilts, decentrations, and airspaces to performance. A final system refocus was assumed by allowing element "E2" to axially translate. As with any tolerance program, it is important to check representative tolerances using real-ray analyses. Certain system perturbations such as misalignment of the rotating housing and fold mirror had to be toleranced separately because of imcompatibility with the present program. Table I summarizes the representative tolerance levels.

The system mechanical parts were designed to be compatible with the recommended element positional tolerances, assuming:

- The elements would be centered in their seats to within ±0. 0005 inch.
- The fold mirror is adjustable in tip, tilt, and location.

Table I. Typical Tolerance Level Ranges

Parameter	Typical Tolerance Levels
Radius	±0.0005 inch (measured accuracy)
Power fit to test plate	Five visible fringes
Surface irregularity	Three visible fringes
Element wedge	0.002 inch TIR
Element tilt	0.002 inch TIR
Element decenter	±0.002 inch
Airspace	±0.002 inch

The optomechanical system assembly and alignment methodology is summarized below:

1) Elements are centered in their 0.01 inch nominally wide bond line area using three mylar shims. They are bonded with RTV 560.

2) Using a separate test station which provides a translating collimated IR source, the focusing lens is adjusted for focus and, if necessary, focal length (to match the detector TDI rate).

3) Using a separate alignment station, the fold mirror is adjusted in tip, tilt, and position. Figure 8 shows one of several possible methods. Using a precision reticle (R_1), an alignment telescope is located on the input optical axis (A_I). Reticle (R_2) is accurately located at a nominal scan mirror facet position and accurately tilted so as to be perpendicular to axis (A_F). The fold mirror is now adjusted so as to center and autocollimate off of the reticle (R_2). (The rotating housing is not in place for this operation.) As noted, other methods are incorporated, such as a reticle in the focusing lens area (R_3) used in conjunction with reticle (R_4) and a reticle in one leg of the rotating housing (R_5). The above allows for complete versatility in making this important setting.

4) The rotating housing is now centered on axis (A_F) by translating it in its adjustable bearings along axis (A_R) to center reticle R_5.

5) The E1/E2 module and the focusing lens/detector is fastened to the optics housing. Incorporation of the scan mirror, focusing lens, and detector forms a complete system.

6) Element "E2" is translated for a final focus adjustment.

Test plans for semiquantitative go/no-go optical module tests

In order to assure success of the optical module approach, it is desirable to perform functional tests, where possible, on each module. In particular, tests have been configured for the E1/E2 module and the rotating housing module. These tests should ideally provide the following:

1) A semiquantitative assessment of performance (i.e., image quality)

2) Determination of the relative focus position of the module

3) Measurement of the module boresight error

If an optical module passes the above "ideal" tests, it should perform acceptably in the system and be interchangeable from one system to another. The test should be rapid and easy to use in a production environment.

A test configuration consistent with the above requirements for the E1/E2 module is shown in Figure 9. A 10.6 µm laser is focused onto a pinhole so as to provide a point source at the focus of an off-axis paraboloid. The module under test is fastened to a precision prealigned reference surface, and a high quality dome is placed in front of the module. A 30 Hz tuning fork followed by a pyroelectric detector is mounted on an X-Y-Z stage, and is used to scan the image. The detector output is displayed on a signal averaging oscilloscope where it is averaged over the previous 30 to 60 scans with an exponentially decreasing weighting. This method provides for noise reduction by virtue of the signal averaging, yet is "active" in the sense that the user very quickly sees the result of an adjustment.

The E1/E2 module is diffraction limited at 10.6 µm (rms wavefront degradation = 0.027), thereby suggesting that a perfect module should yield a perfect edge trace. In use, a yet-to-be-defined degradation will be considered acceptable based on the go/no-go test philosophy. Appropriate adjustment of the X-Y-Z stage will permit measurement of focus and boresight error. The tuning fork is easily rotatable about the optical axis for measurement in any azimuth. The test has the growth potential to MTF measurement by outputting the edge trace from the signal averager to a minicomputer where the appropriate transformation could be made.

A similar test is configured for the rotating housing optics.

Summary and Conclusions

This paper has summarized the various optical design and engineering related considerations which have been applied toward the generation of an IR scanning system. The final goal of a cost-effective, yet production-compatible, system was derived by appropriate engineering at the various design phases:

- Optical/Mechanical Design - Modular approach
- Lens Element Assembly - Design and tolerances must be compatible with centering elements in their cells
- Special Fixturing - Alignment of critical components (i.e., fold mirror) with aid of special test fixture
- Go/No-Go Module Test - Test stations to qualify individual optical modules

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The significant efforts of Bruce A. Cameron and Donald W. Burt of Hughes/Canoga Park and Ronald K. Kimmel of Hughes/Culver City are greatly appreciated.

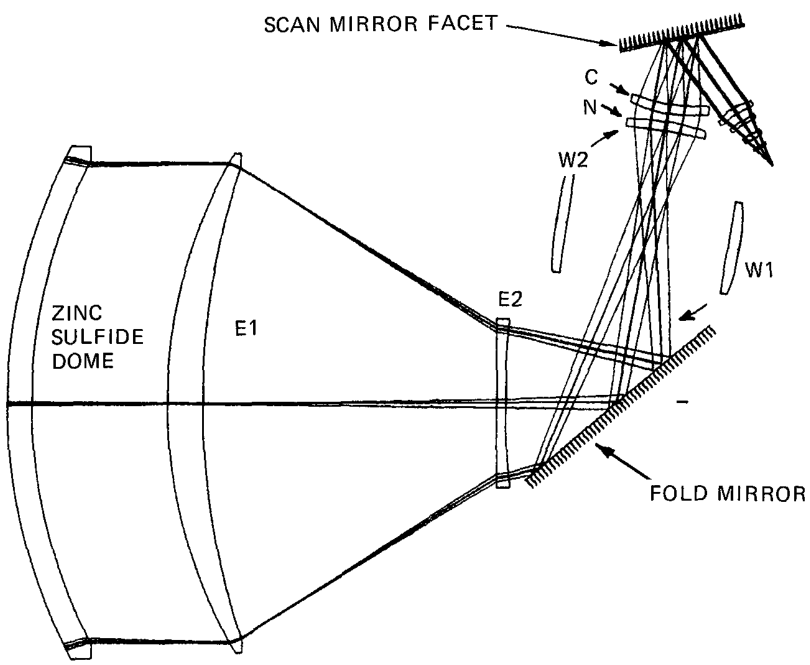


Figure 1. Design form of advanced development IR scanning system

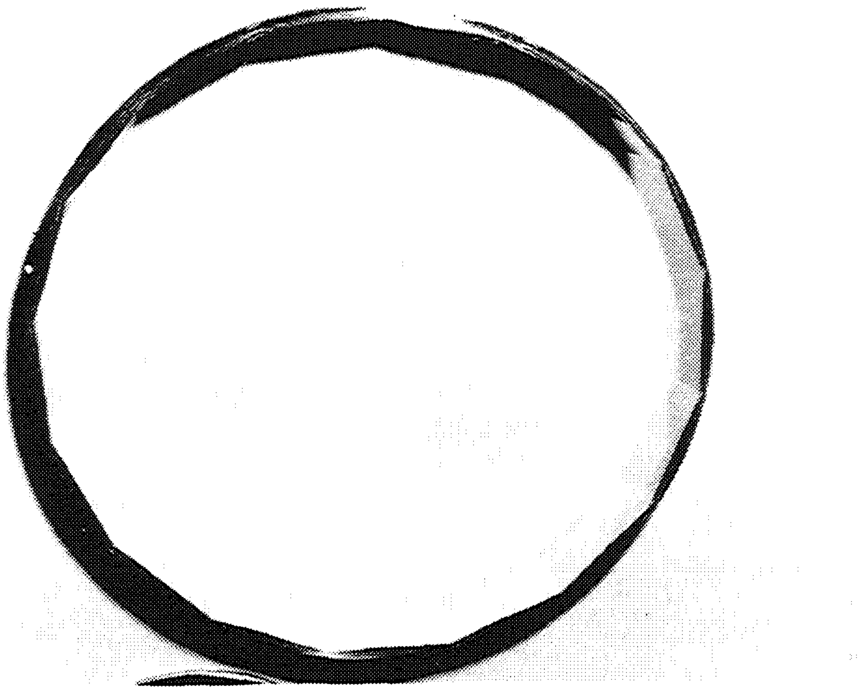


Figure 2. Typical multifaceted scan mirror

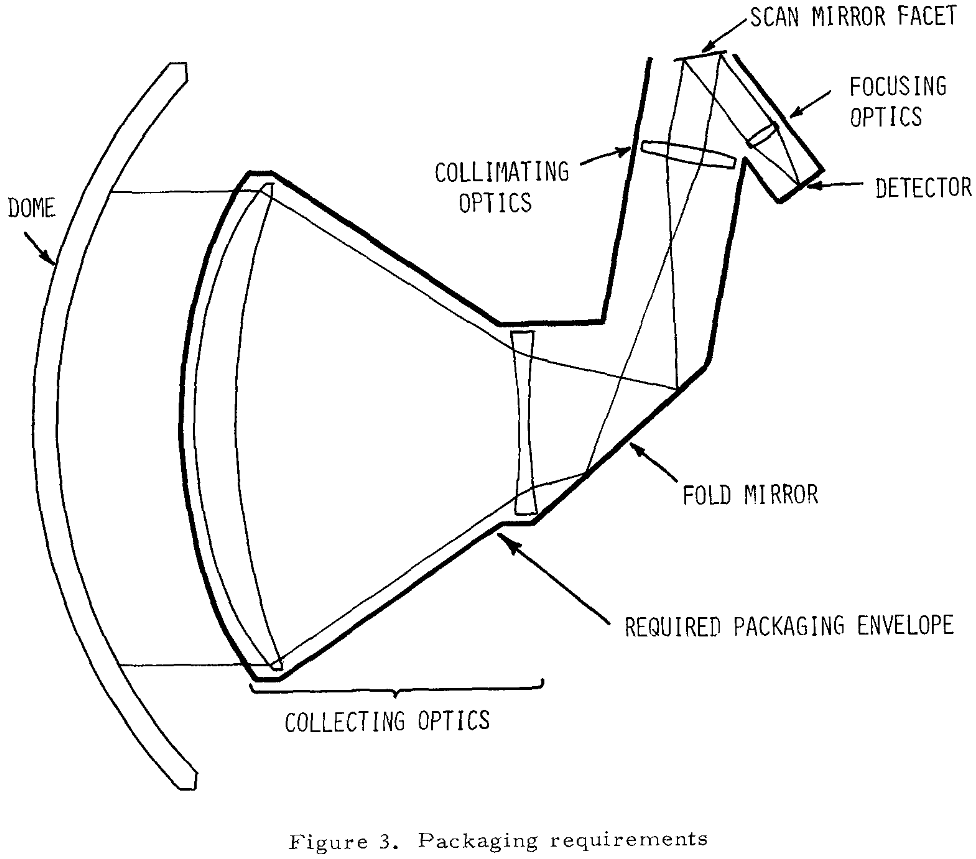
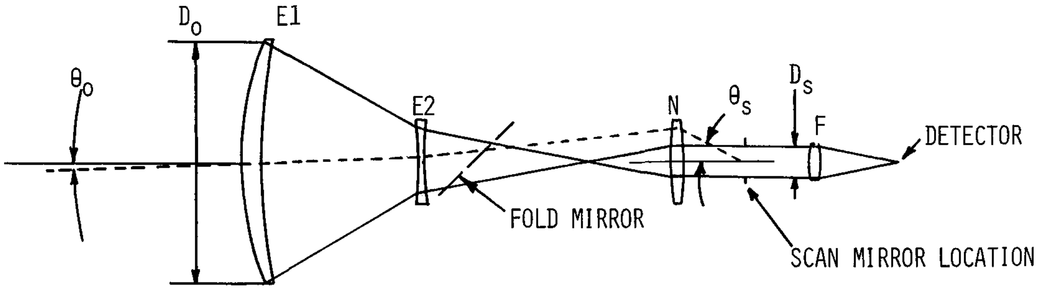
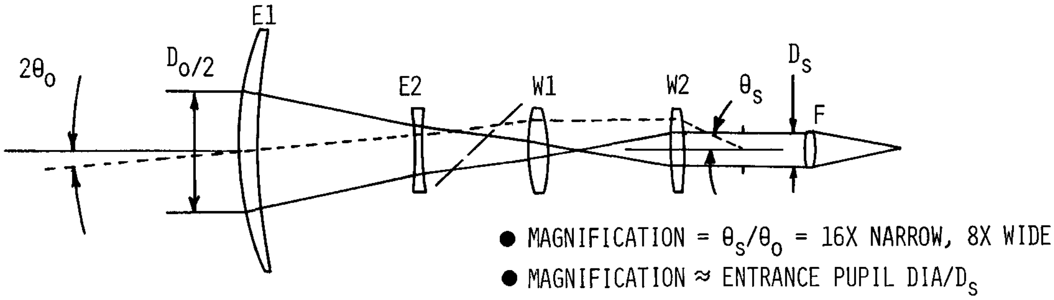


Figure 3. Packaging requirements



a) NARROW FIELD



b) WIDE FIELD

Figure 4. First-order relationships

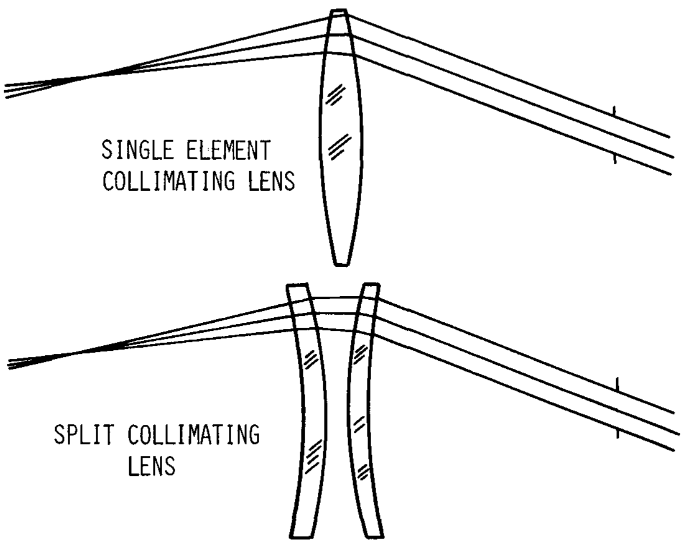


Figure 5. Split form of collimating lens

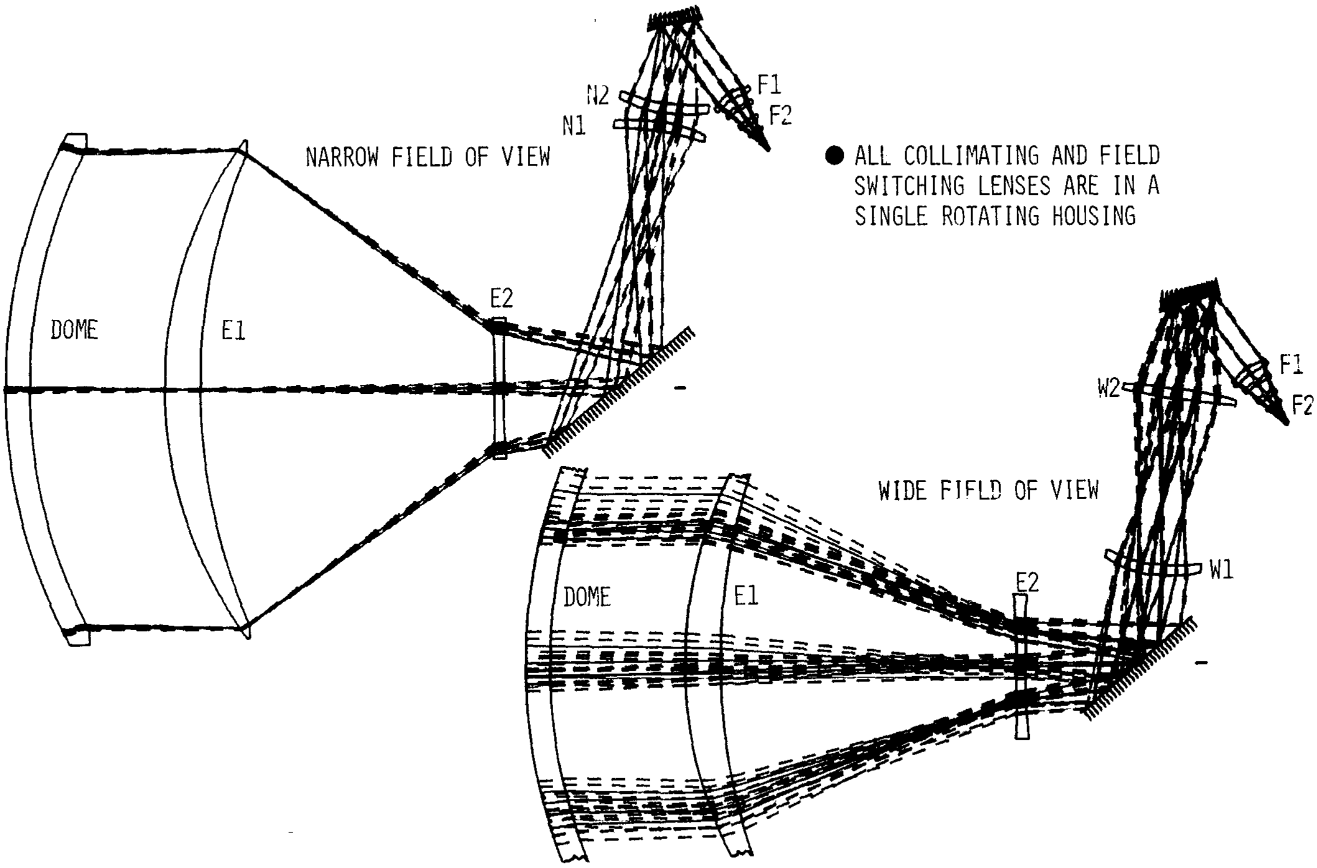
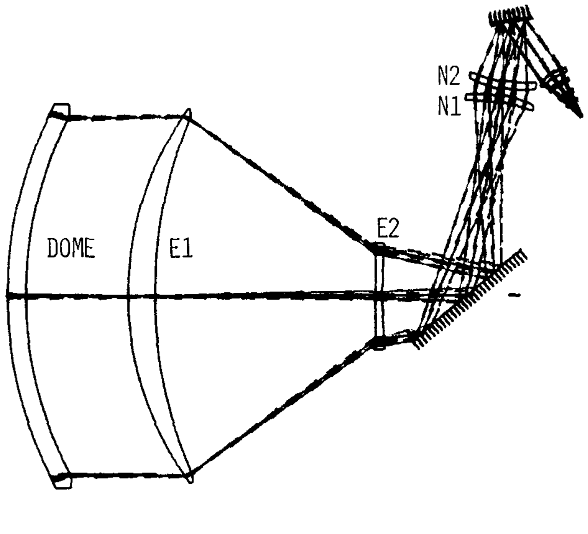
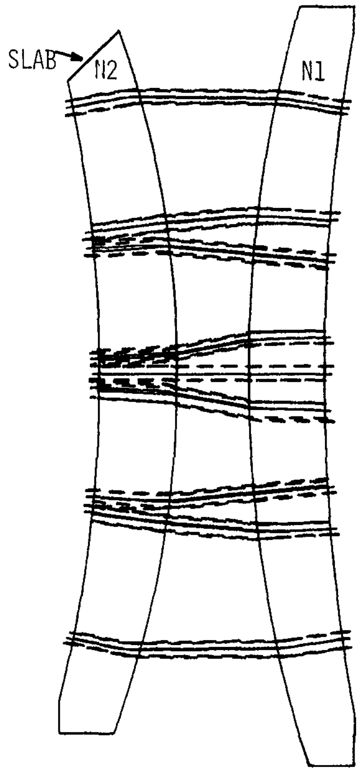


Figure 6. Final optical design



a) ENTIRE NARROW FIELD SYSTEM



b) COLLINATING ELEMENTS ONLY

Figure 7. Ray trace analysis for aperture sizing

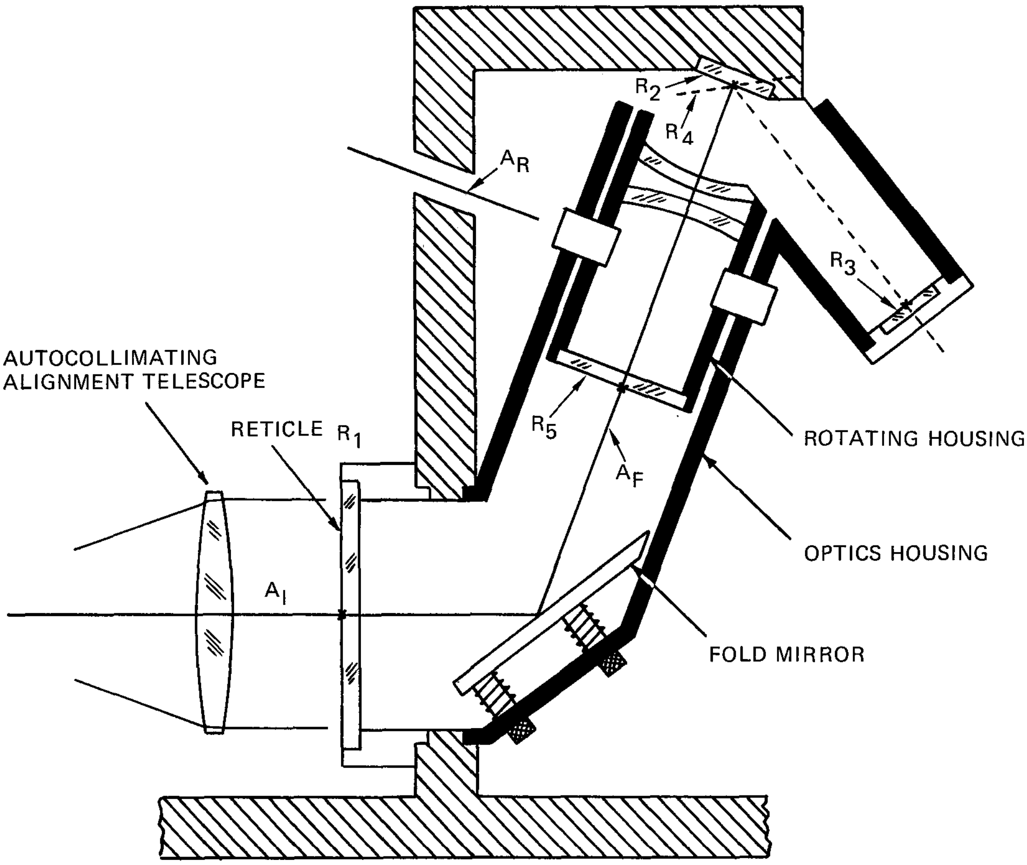


Figure 8. Alignment fixture for aligning fold mirror

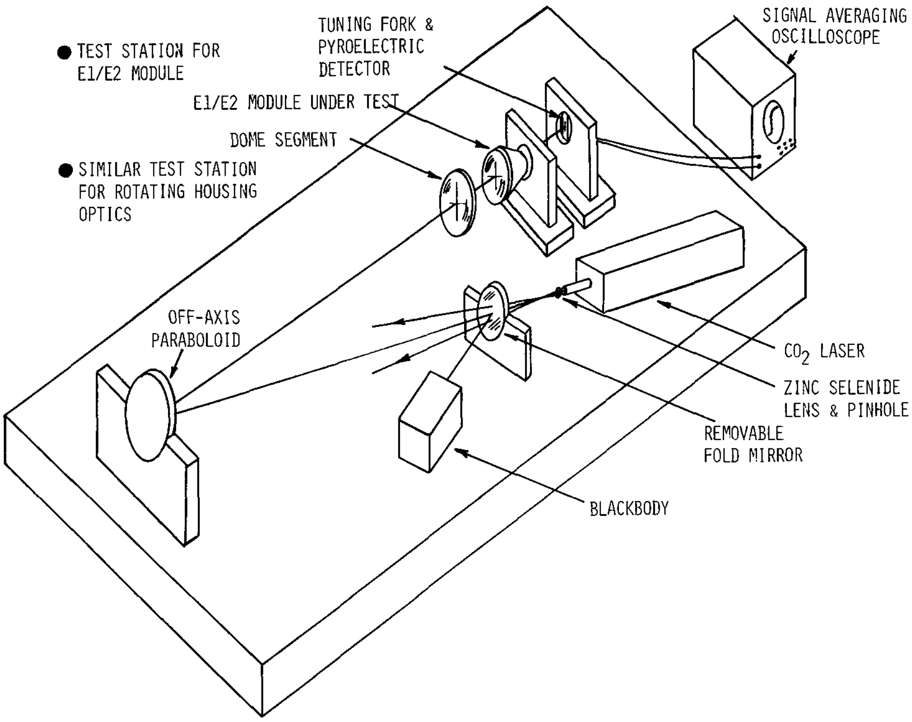


Figure 9. Test station for E1/E2 module

Question and Answer from the Floor

Question: Did you take Detector Narcissus effects into account in the optical design?

Answer: Yes! (a) The CODE V software permits dilution of the narcissus blur. This was used during optimization. (b) Following optimization a complete narcissus study was made.