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Optomechanical design considerations in the development of the DDLT laser diode collimator

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ABSTRACT

A laser diode collimator objective was developed in support of the Direct Detection Transceiver program. Close attention to optomechanical design issues including athermalization, alignment, selection of materials, mounting of elements, and hermetic sealing of the assembly was necessary to insure that the desired optical performance was maintained in space deployment.

1. INTRODUCTION

The optomechanical design considerations required in the development of a five-element laser diode collimator (LDC) are presented. The LDC was designed and built in support of the Direct Detection Laser Transceiver (DDLT) program. The DDLT program was established to conduct free space laser communication experiments from aboard the ACTS satelite.

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* Previously with SBAO at time this work was conducted.
** Previously with TRW at time this work was conducted.

The optomechanical design of the LDC was performed at Santa Barbara Applied Optics (SBAO) under contract to the Space and Defense Division of TRW. The optical design, as well as all systems engineering, was performed by TRW. The optomechanical design responsibilities, as well as the fabrication and assembly of actual units was conducted at SBAO based on the specifications outlined in the Statement Of Work supplied by TRW.

SBAO has delivered two sets of LDCs to TRW. In 1985 lenses designed specifically for laboratory breadboard use were delivered. These lenses, although not destined for use in space, were designed for 1/10 wave peak-to-valley (@ 1/40 wave rms) wavefront error. These units were followed in early 1988 with a similar design which had the added requirement to operate in the free space environment. Comparisons between the two lens systems are given illustrating the different approaches taken based on eventual usage.

The LDC's function is to collimate the highly divergent radiation emitted from the laser diode. To acheive the desired systems performance, close attention was required in the optomechanical design effort to accomodate the environmental stresses imposed on the LDC in space deployment. This paper describes the approach taken in design and fabrication to meet the specified performance goals.

2. DDLT SYSTEMS REQUIREMENTS

The DDLT was intended to be an experimential laser diode transmitter and receiver added to the LITE system aboard the ACTS satellite. DDLT was to use LITE's pointing and tracking system to direct a two-way link between the ACTS geosyncronus orbit and either a ground-based station or a low earth orbiting platform in a series of communication experiments.

The DDLT transmitter combines the output of three laser diode/collimator modules of varying wavelengthes through wavelength division multiplexing (using dichroic beamsplitters). One laser is operated at a time. The other two are intended as backups in case of laser failure or when the primary laser's power drops below a specified threshold with time. In this manner systems lifetime requirements are insured. Selected system level requirements imposed on the DDLT Transceiver are shown in Table 1.0.

Table 1.0 Selected DDLT Systems Requirements

Wavefront error:	1/20 wave rms
Power output:	60 mW
Beam diameter:	4.6 mm
Alignment/drift:	Not to degrade wavefront over above spec.
Temperature range:	4-24 degrees C (operating) -40 to +70 degrees C (storage)
Contamination:	Hermetically seal critical components
Radiation:	Maintain transmission over lifetime

3. COLLIMATOR REQUIREMENTS

Certain optomechanical considerations not normally associated with land based systems must be be considered in the design of LDCs destined for free space. These include isolating the Laser Diode Capsule from the space environment, manufacturing the LDC from space qualified materials and designing the assembly to achieve the desired performance in the space environment.

The specific collimator requirements were derived from the systems requirements, the characteristics of the selected laser diode (divergence, wavefront, power, etc.), and from previous experience building and testing similar units for other applications. The principle DDLT collimator requirements which were imposed on SBAO in the manufacture of the LDCs are summarized in Table 2.0.

Table 2.0 DDLT Collimator Requirements

Wavefront error:	1/40 wave rms (over FOV)
FOV:	+/- 1 degree
Bandpass:	863-874nm
Transmission:	>95%
Hermetic sealing:	< 5X10-7 atm cc/sec helium
Element surface quality:	20-10, per Mil-O-13830 10-5, on surface nearest laser diode
Element surface roughness:	<20 angstrom rms
Metallic surface finish: (on mating surface to adjacent laser capsule)	8 microinch

In allowing for errors in the rest of the system (primarily budgeted to focus alignment/drift), the goal of 1/40 wave rms was established for the LDC optical quality. During previous programs conducted at TRW, several commerically available laser diode collimators and microscope objectives had been tested for wavefront quality and alignment sensitivity on a phase shift interferometer. Although none were expected to quite meet the wavefront goal, it was desirable to determine what level of quality and alignment sensitivity was readily available, as well as to determine reasonable goals for a custom optics design.

The original optical design (developed at TRW) was a four element system incorporating a cemented doublet. Due to concerns over radiation hardness for both glass types used and some uncertainty over the cement, it was decided to use an all fused silica design (the best material in regard to radiation hardness and thermal compatibility to Invar). This meant eliminating the doublet and going with an completely air-spaced system. As soon as the four element system was re-optimized, it become obvious that alignment tolerances (centration, tilt, and spacings) were beyond reasonable manufacturing capabilities. By adding a fifth element, these tolerances dropped to a reasonable range.

Early design work produced two collimator systems utilizing fused silica as the lens material. To alleviate alignment problems experienced with commerically available LDCs, these systems were designed with a wavefront error of less than 1/40 wave rms over a 1.0 degree field of view, taking into account estimated manufacturing errors.

This work was the basis for the development of a five-element LDC designed specifically for laboratory breadboard testing. The result was a collimator which was relatively easy to align to the interferometer or laser diode and a resultant wavefront quality which measured less than 1/50 wave rms for both breadboard units built.

Other investigators have reported developing LDCs of similar quality using other materials (such as cerium-doped glass) or fewer elements[1]. However, in light of the excellent performance observed with the breadboard units, as well as the radiation hardness and athermalization requirements imposed on the system, it did not seem advantageous to pursue an alternative design.

For use in DDLT, very slight design changes were incorporated in the breadboard LDC design to accomodate a different wavelength region and a slightly different laser divergence. This LDC is shown in Figure 1.0. It is basically the same five element, all fused silica system, except that it also incorporates a protective plano-plano window.

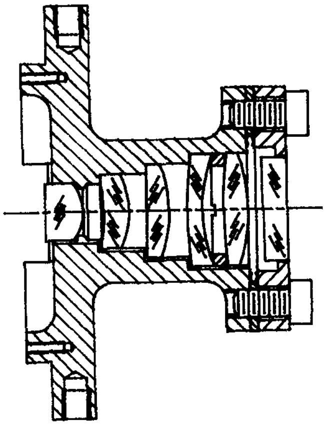

FIGURE 1.0
DDLT LASER
DIODE COLLIMATOR

All element surfaces, with the exception of the exterior protective window are spherical. No aspherics are utilized. The window is designed with slight wedge between the two plano surfaces to minimize the energy reflected back toward the laser diode.

Further testing was conducted on the breadboard LDCs to varify estimated beam wander due to thermally induced laser diode motion in the DDLT laser diode module. The measured angular drift and wavefront quality at the various angles fell within previously estimated system alignment and wavefront error budgets.

Optical surface quality was a major concern in order to minimize the diffusion and loss of energy through scattering. Surface roughnesses of 20 angstroms rms maximum were specified. Special manufacturing processes to control subsurface fracture during the lens grinding operation were utilized and surface roughnesses of better than 5 angstroms rms were achieved. The scratch and dig specification was held to 20-10 per MIL-O-13830 on all surfaces except the last surface nearest the laser diode , where the quality was held to 10-5 to avoid obscurations in the small clear aperture of that surface.

To maximize energy transmitted through the system from the laser diode, high transmission was required over the specified spectral bandwidth. For the early breadboard units transmissions of 98% per surface were deemed adequate. Quarter wave MgF_2 coatings were specified on the low index fused silica elements to attain this. The transmission specification was increased to 99.6% per surface on the Space Deployable units necessitating a multilayer antireflection coating.

4.0 KEY OPTOMECHANICAL ISSUES

In this section the key optomechanical design issues are discussed. These included establishing the error budget, the selection of materials based on thermal and environmental concerns, lens mounting options, shock and vibration considerations, hermetic sealing of the lens system, and venting of internal cavities.

4.1 Establishing the error budget

The error budget for a lens system is based on a balance between two factors, optical performance and optical shop fabrication capabilities[2]. The lens designer must account for the degree of precision which is attainable at a reasonable cost within the optical shop when determining the distribution of fabrication errors. In this way the desired performance of the optical system can be met in the most economical fashion.

In a collaborative effort such as this it is essential that clear lines of communication are maintained between the optical designer and optomechanical engineer to insure the accurate transfer of information. In this situation the lens design effort was conducted at TRW while optomechanical design and fabrication was the responsibility of SBAO. The final tolerance analysis and resultant error budget was not completed until a clear understanding of the optical shop tolerances at SBAO was relayed to the optical designers at TRW. This required the close cooperation between the two organizations to engage in an itterative process in which the distribution of manufacturing tolerances was established relative to desired optical performance as well as to the optical shop capabilities existing at SBAO.

The final error budget for the DDLT LDCs is shown in Table 3.0. Airspaces were held to a tolerance of +/- .001"(.025mm) and lens thicknesses to within +/- .002"(.050mm). These values were considered well within manufacturing limits. The design analysis indicated no significant impact on lens performance with a distribution of spacings within these limits. In the case where a lens was required to grow into an airspace, a space was chosen that had a minimum impact on performance.

Table 3.0 Error Budget

Radius test plate fit	1 Fringe
Surface irregularity	1/4 Fringe
Index variation	.0002
Surface tilt	3 Arc Minute
Thicknesses	.050mm(.002")
Airspaces	.025mm(.001")

Schlieren Grade Fused Silica (Corning 7940) was selected for all optical elements. This choice was strongly influenced by the athermalization requirements imposed on the assembly. This is discussed in more depth in a later section. Prior to the manufacture of the early breadboard units, the index of refraction of fused silica was measured to six decimal places. It was found that the measured values agreed very closely with the catalogue values and so the optical design was not modified to correct for this small difference.

In both cases, for the early breadboard design and for the DDLT units, close attention was given while fitting SBAO test plates to control the amount of energy reflected back toward the laser diode.

4.2 Athermalization

Athermalization is of primary concern with space deployed optical assemblies. As shown in Table 1.0 the typical operating temperature range specified for space deployed LDCs is 4-24 degrees C (277-297K), and a storage temperature range of -40 to +70 degrees C (233-343^{o}K) must be considered in design.

Performance degradation due to differential expansion of the lens mount and elements was avoided by selecting materials of similar coefficients of thermal expansion. Fused silica (CTE =.54X10^{-6}/degree C) and Invar (CTE =.56X10^{-6}/degree C) are an excellent match. Invar was also selected to match the CTE of the adjacent laser diode capsule. The worst case compressive hoop stresses were evaluated. With the materials selected, compressive stress on the order of 50-100 psi were calculated at the extreme storage temperature. This is far below the compressive stress levels where strain in the optical element might result in birefringence[3].

4.3 Lens Mounting Options

4.3.1 Breadboard laser diode collimator The mounting scheme used on the breadboard LDCs, shown in Figure 2.0, differed appreciably from that used on the later DDLT LDCs. In the breadboard design, the lens elements were stacked within the lens barrel using spacers and cells to maintain the desired airspaces. The entire assembly was then locked in place with a retaining ring. The ring was then tacked in place using an epoxy.

The lenses were optically trued under microscopes and diameter tolerances were held to +.0000",-.0005". In cases where the elements were bonded into cells they were also trued to the cell diameter. Cells, mount, and spacer diameters were held to +.0005",-.0000" to minimize any decentration of the lenses. All lens seats were held perpendicular to the optical axis to within .0002" to minimize lens tilts.

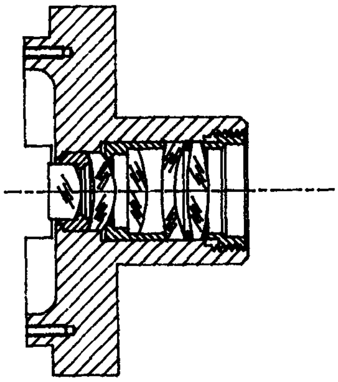

FIGURE 2.0
BREADBOARD
LASER DIODE COLLIMATOR

The lenses were then tested for centration and tilt in final assembly and the retainer tightened with only enough torque to secure the lenses, without deforming their surfaces.

A disadvantage with the breadboard design is that it is not possible to varify the concentricity of each element or the airspaces between elements in the final configuration since the lenses are loose until the retainer is tightened.

An additional shortcoming with this approach is poor shock stability. Since the elements are relatively unrestrained, damage or movement in a high shock or vibration environment is a possibility. This was not a consideration with the early breadboard units however, since they were destined to a somewhat benign environment.

Finally, the breadboard design had no requirement for hermetic sealing, again due to the application. This was a critical design requirement with later units. In regard to optical performance, these breadboard LDCs performed quite well. As stated previously, measurements done on a phase shift interferometer at TRW indicated that these assemblies had on-the-order of 1/50 wave rms wavefront error.

The remainder of this paper concentrates primarily on the later development of the DDLT LDCs.

4.3.2 DDLT laser diode collimator The high performance required of this collimator (1/40-wave rms wavefront error) required accurate mounting of the elements to assure positional accuracy along the optical axis as well as minimizing tilts and decenters. Various lens mounting schemes were considered in the design phase; these including using retainers and spacers similar to the previous design or possibily mounting elements in cells. In the end, it was felt that best control could be maintained by mounting the elements individually on machined seats (Fig 1.0) in the lens barrel.

The lens seats were machined concentric to one another, as well as to reference diameters, in a single machining operation using a precision numerically controlled (NC) lathe. Decenters introduced from misalignment during machining were thus eliminated. The lens seats were held perpendicular to the optical axis within .0002", equivalent to 2 min. tilt over a typical 0.294" (7.5mm) diameter.

As the elements were assembled into the housing, concentricity to the optical axis was varified optically by observing the runout of the image produced at each surface. The lens elements were edged and bevelled to close tolerances to avoid introducing wedge or tilt. The lens diameters were held to within +.0000",-.0005" while the lens seats were held to within +.0005",-.0000". Minimal radial separation between lens element and mating ID was .0002" (.005mm).

An additional advantage to this approach is excellent stability in a high shock and vibration environment. Once bonded, lens elements remain fixed in their desired position.

Axial location of the elements was maintained by machining the seat depths to a tolerance of +/-.001" from the reference surface. Lens elements were selected for thickness to maintain airspaces as required in the lens design. The tight tolerances specified for the lens element thickness, +/-.002" (.05mm), resulted in a higher rate of attrition for center thickness than would generally be acceptable for medium to large production quantities. However, since this order was for less than 10 units, fabrication of optical elements was not the most significant cost driver.

In the fabrication of optical elements the number of elements produced is a function of the number of elements required to fill a polishing or grinding tool. This, in turn, is dictated by the radius of curvature being worked as well as by the part diameter[4]. As a result, a sufficient number of elements were fabricated to allow for the selection of elements at or near the nominal thickness.

In a large volume production situation a redistribution of fabrication tolerances might be considered. This could possibly result in looser constraints on thickness. An alternative approach such as lathe assembly[5] might be considered. Here airspaces are optimized for each unique assembly using the lens design program to compensate for variations in element thicknesses. The cost tradeoff between additional in-process engineering as well as the need for additional machining operations would have to be evaluated relative to accepting a higher rate of attrition of optical elements.

4.4 Sealing of the laser diode capsule

The LDC acts as the front seal for the laser diode capsule. The entire laser diode capsule must maintain a leakrate of less than 5x10-7 atm cc/sec helium in the operating environment. Compliance to this specification was a design and test requirement.

To achieve the desired seal, two interfaces required sealing. These were between the LDC and the adjacent capsule as well as between the LDC housing and the retainer in which the window was mounted. For both cases Metal C-Rings (Fig. 3.0) were utilized to achieve the desired seal. C-Rings provide excellent sealing capabilities in high vacuum and are especially useful in space applications since no organic materials are utilized which may eventually degrade. When the slot of the C-Ring is installed toward the high pressure side, the pressure exerted against the C-Ring forces the metal walls of the ring against the mating sealing surfaces.

MATERIAL: INCONEL X-750
GOLD PLATE .0015 THICK

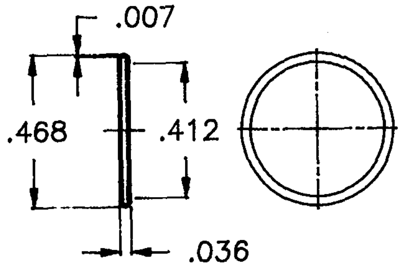

FIGURE 3.0
METAL C-RING
INTERNAL PRESSURE

A soft metal plating on the exterior of the C-Ring improves the sealing capability by conforming to the surface irregularities in the metal mating surfaces. In this application Inconel X-750 was selected as the base metal for the C-Ring. A .0015" gold plating was added.

Other mechanical parameters which must be specified in Metal C-Rings applications include controlling the compressive loads on the C-Ring, and specifying the surface finishes on the metal mating surfaces. The compressive seating load is controlled by specifying the depth of the seat in which the C-Ring is installed and the ring free-height.

Surface finish requirements are dictated by the application. For high vacuum applications a 8 microinch finish is recommended. Also, to minimize the possibility of leakage, all machining grooves should be concentric to the C-Ring. Radial machining grooves or scratches should be avoided as they may compromise the seal.

Initially, the housing was designed with a seat to locate the C-Ring (Fig 4.0). However, machining to the desired finish was difficult in a pocket of such small area. This was accentuated by the poor machinability of Invar.

The configuration was later modified to that shown in Figure 5.0 in which the mating surface was relieved to the depth of the seat and a spacer used to control the seating load. The machinist was then able to turn the surface to the desired finish relatively easily.

Further applications data regarding C-Rings can be obtained from the manufacturer.

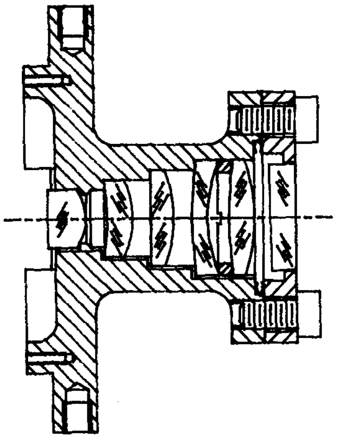

FIGURE 4.0
ORIGINAL DDLT
LDC CONFIGURATION

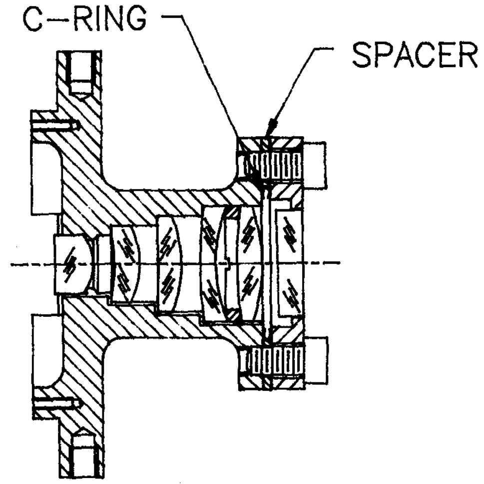

FIGURE 5.0
MODIFIED DDLT
LDC CONFIGURATION

4.5 Window/retainer subassembly

The plano-plano window was hermetically sealed in the retainer in a high temperature brazing operation. The seal between the window and retainer was tested and certified to 1X10-9 atm cc/sec helium by the vendor. The primary purpose of the window/retainer assembly was to act as the final seal for the LDC. The C-Ring sealed against the metal surfaces of the retainer and housing, thereby providing the final exterior seal to the laser diode capsule.

4.6 Venting of internal cavities

Since the laser diode capsule is a sealed unit it was necessary to vent all airspaces between elements. This was accomplished by machining a slot intersecting the lens seats using Electric Discharge Machining (EDM). With EDM a burrfree finish is produced and the structural rigidity of the housing is minimally impacted since the slot is of smaller cross-section than would be obtainable with conventional techniques.

5.0 ASSEMBLY OF THE DDLT LASER DIODE COLLIMATOR

A primary concern during assembly of the LDC was maintaining the centration of the optical elements. If, for example, a lens of .294" dia. and .97" E.F.L. was tilted by .0005", due perhaps to dirt or a burr, this would be equivalent to a decentration of the image at the element's focal point by .0016". This degree of error could lead to substantially degraded wavefront quality. To insure the cocentricity of elements, each lens was monitored optically during the assembly process.

After all cleaning was completed and concentricity in seats varified for each element, final assembly could go forward. Each element was bonded to its seat using a space qualified epoxy, three places 120 degrees apart, around the lens periphery. Concentricity was revarified before proceeding to the next lens. Lens No. 5 (see Fig. 1.0) was somewhat of an exception in that a spacer was used to axially locate the lens in place of a machined seat. This was due primarily to edge thickness considerations.

Quite early in the assembly process it became apparent that the proper seating of the elements was hampered due to buildup, or "Smut", remaining from the black oxide process. This condition was quite severe on the Invar components. Black oxide had been selected to provide corrosion resistance and reduce reflections without introducing dimensional changes. However, after our experience cleaning the housings, evaluation of possible alternative finishes which might be easier to work with is recommended.

The window/retainer assembly was then attached. Critical at this point was varifying that all mating surfaces were clean and not compromised by scratches or burrs. Also, care was necessary to insure that pressure was uniformly applied as the retainer was bolted in place.

The assemblies were tested for fine leak and then subjected to the environmental tests shown in Table 4.0. They were then retested for leakage prior to delivery to the customer.

Table 4.0 DDLT Test Matrix

Housing fine leak	Helium leak test to varify a leak rate of less than 5X10-7 cc/sec
Temperature cycling	-40 c to +75 c 30 minute dwell at temperature extremes
Thermal soak	-40 c, 12 hrs. +75 c, 12 hrs.
Housing fine leak	Leak rate < 5X10-7cc/sec
Optical performance	< 1/40 wave rms wavefront error

We ran into some difficulity when testing the first LDCs for fine leak. We were unable to hold a seal of below 1X10-5 cc/sec. After considerable scrambling around, retesting units and reevaluating our design, it was determined that the problem was due to insufficent gold coating on the C-Rings. Less than half the specified thickness of gold had been deposited. Once the rings had been replated, achieving the desired leakrate was straightforward.

Two of the DDLT Laser Diode Collimators delivered to TRW were tested for wavefront quality during December of 1988. The assemblies were tested on aSira Phaseshift Interferometer in a doublepass mode. Wavefront errors typically of the order of 1/50 wave rms were recorded over the one degree field of view. In no case did the measurements exceed 1/40 wave rms. Again, it should be realized that these are doublepass figures, so the performance of the assemblies can be assumed to be significantly better in operation.

6.0 POTENTIAL DESIGN IMPROVEMENTS

6.1 Alternative design for the window/retainer assembly

Although an excellent exterior seal was obtained with the window/retainer configuration described in this paper, some design improvements might be considered. The need for brazing the window and retainer at high temperatures induces higher compressive stresses on the window than is desirable. The brazing operation is necessary in this configuration since the C-Ring seal is between the retainer and housing.

An alternative approach explored at SBAO is to place the C-Ring between window and housing (see Fig 6.0). In this configuration, a hermetic seal between the window and retainer is not required. The sealing takes place between the window and flange. A thin layer of gold deposited in vaccum on the window is added to improve the seal between the polished window and the C-Ring.

The flange face must be machined at an angle to compensate for the wedge in the window. The window itself, is mechanically constrained by the retainer. A plastic washer is placed between the window and retainer to minimize the possibility of fracture. Compressive stresses on the window would be minimal and fabrication of the unit simplified.

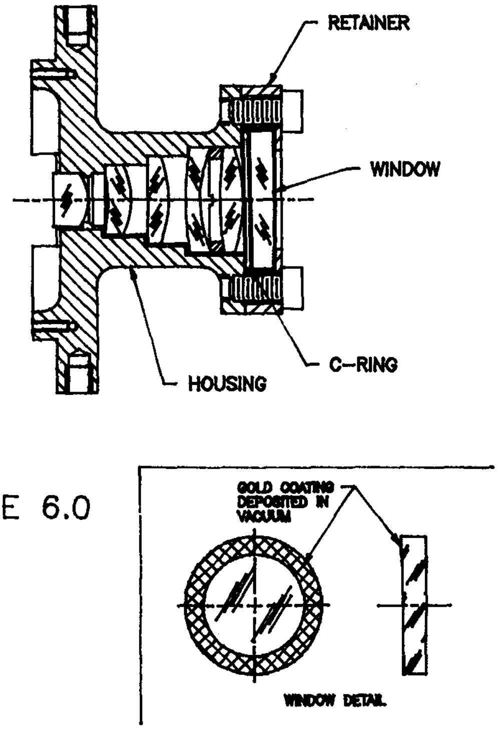

FIGURE 6.0

7.0 ACKNOWEDGEMENTS

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