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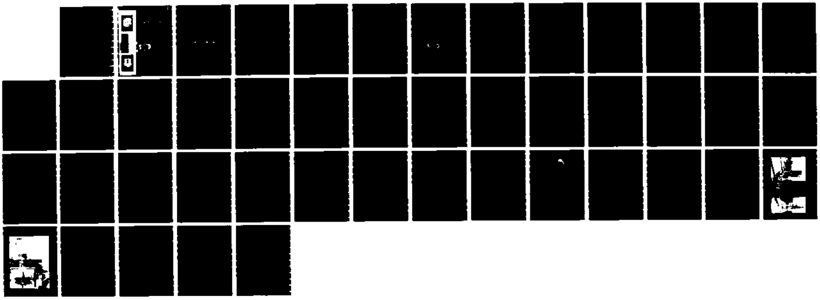

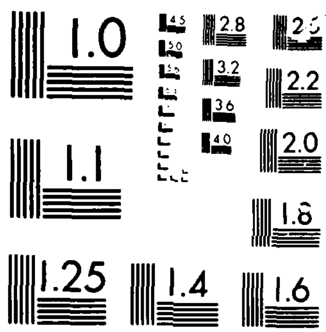
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FRANK J. SEILER RESEARCH LABORATORY

JSRL-TR-86-0002 MAY 1986

OPTICAL ROTATION SENSORS

FINAL REPORT

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PROJECT 2301-F1-68

AIR FORCE SYSTEMS COMMAND

UNITED STATES AIR FORCE

FJSRL-TR-86-0002

This document was prepared by the Laser Division, Directorate of Lasers and Aerospace Mechanics, Frank J. Seiler Research Laboratory, United States Air Force Academy, Colorado Springs, CO. The research was conducted under Project Work Unit Number 2301-F1-68, Optical Rotation Sensors. Sequentially, Major Gerald L. Shaw and Major James R. Rotge' were the Project Scientists in charge of the work.

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This report has been reviewed by the Commander and is released to the National Technical Information Service (NTIS). At NTIS it will be available to the general public, including foreign nations.

This technical report has been reviewed and is approved for publication.

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Research efforts were concentrated on passive ring laser rotation sensor technology. Initial efforts were performed on supportive projects, e.g., laser stabilization, followed by a 0.62 m^2 passive resonant ring laser gyro (PRRLG), leading to the development of a 60 m^2 system mounted on the pneumatically supported isolation test platform (Iso-Pad) at FJSRL. Numerous sub-system tasks and a feasibility 0.62 m^2 PRRLG were completed, supporting projections of very high resolution performance by a large 60 m^2 PRRLG. The expected performance of the large PRRLG, on the order of 10^{-10} ERU (earth rate units), would provide an accurate error model applicable to Air Force operational ring laser gyros, a new source of geophysical data, e.g., earth wobble and variations in earth rotation, a proven design concept applicable to Air Force sensor needs as reference to MX instruments tests, and relativity experiments.

This report documents the many accomplishments leading to, and the status of the large PRRLG at the date of the PRRLG stop order, November 1985.

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1. INTRODUCTION

As part of an ongoing program to develop optical rotation sensors for Air Force applications, FJSRL undertook construction of a 60 m^2 Passive Resonant Ring Laser Gyroscope (PRRLG). Predicted performance of this device was shown to be as good as $4x10^{-10}$ earth rate units (ERU) ($2.9x10^{-14}$ rad/s). As such the device would be useful for error source studies, improved angular rate sensors, geophysical investigations, relativity experiments and potentially gravity wave detection.

The resonant ring is supported by a 450,000 (205,000 kg) pound reinforced concrete isolation test platform. The platform is floated on pneumatic isolators on a seismic base and actively controlled to provide isolation to vibration in six degrees-of-freedom to about 10^{-8} g and two axis tilt attitude stabilization (with respect to local vertical) to better than 10^{-3} arc seconds.

This report discusses the conceptual overview of the large PRRLG, the isolation test platform, performance predictions for the gyro, planned experiments, the initial performance data, and status as a result of the stop order on 27 November 1985. The report also covers the development of the feasibility demonstration model of the 0.62 m^2 PRRLG and over 20 support projects performed by university professors and students, USAF Academy faculty, Air Force reservists, USAF Academy cadets, and Air Force Institute of Technology (AFIT) students.

2. BACKGROUND

Optical rotation sensing dates back to the early 1900's. In 1913, George M.M. Sagnac is credited with first demonstrating rotation sensing by optical means.[1] He was able to detect ($\sim$0.07 fringe) a rotation rate of $\sim$4 rev/sec with his apparatus. In 1925, Michelson and Gale were first to actually detect earth rotation by means of a large scale "Sagnac effect" interferometer.[2] Their device consisted of a rectangular system of pipes approximately 650 m x 320 mg evacuated to reduce the effects of a turbulent medium. They reported a fringe shift of $\lambda/4$ due to the earth's rotation as measured at the latitude of their experiment near Chicago, Illinois.

New interest in the "Sagnac Effect" was apparently sparked by the invention of the gas laser. In 1961, Rosenthal[3] proposed using a laser and resonant optical cavity to allow a much more sensitive measure of inertial rotation. Macek and Davis built the first active ring laser gyroscope in 1963.[4] In 1977, Ezekiel and Balsamo first reported on the operation of a PRRLG as a means of avoiding the lock-in problem associated with active ring lasers at rotation rates near zero.[5] Balsamo continued his research to minimize or avoid this dead-band phenomena while at the Frank J. Seiler Research Laboratory (FJSRL).[6] Shortly after his arrival at FJSRL he suggested that a large PRRLG be built at the Seiler Laboratory. The Large Passive Resonant Ring Laser Gyro (LPRRLG) program at FJSRL was initiated in 1982; the design concept and construction status were described by Major Gerald Shaw and Mr. Bill Simmons in August 1984[7] and Principal Investigator, Major James Rotge', presented a status report at the Stuttgart, FRG, Gyro Technology Symposium in September 1985.[8]

In November 1985, after reviewing costs required to complete this ambitious project and near-term Air Force inertial sensing requirements, the Air Force Office of Scientific Research (AFOSR), the sponsoring organization, terminated the program.

3. RELEVANT AIR FORCE MISSION

The instant start capability and high acceleration and vibration tolerance of optical gyros make them ideal devices for use in tactical and strategic missiles. These same characteristics plus a potential for higher reliability, lower cost, and increased maintainability make optical gyro technology attractive for aircraft and ships as well.

3.1. USAF DEFICIENCY

Increasingly difficult demands are being made on inertial reference technology by weapons delivery systems. Vehicle attitude, attitude rate and linear motion are required in addition to the traditional navigation function of velocity and position. At project initiation, attitude rate sensing requirements were identified for the spectrum of Air Force applications over a range of 10^{-9} to 10^{-1} rad/s (10^{-5} to 10^{3} deg/hr).

From 1983-1985, Air Force requirements of about 10^{-10} rad/s (10^{-6} deg/hr) in precision pointing, ground based test equipment and geophysical data accuracy were identified. Other non-Air Force, but scientific and technology objectives of even greater precision were also identified.

Optical rotation sensors are attractive because of the promise of lower cost, higher reliability and increased maintainability, and because they are ideal devices for strapped down inertial navigation systems. These devices have a wide dynamic range with inherently unlimited rate capability, excellent scale factor linearity, long term stability, insensitivity to acceleration and vibration, and a precisely defined input axis.

The most advanced of the optical rotation sensors is the active ring laser gyro (RLG); but it has not yet reached the level of performance afforded by conventional gyros. The major obstacle limiting the performance of the RLG has been frequency lock-in. The usefulness of the ring laser gyro is predicated on the measurement of a frequency difference between two propagated counter-rotating beams of light (CW and CCW). This frequency difference is proportional to the inertial rotation about an axis normal to the plane of the ring. At low rotation rates, backscatter from the reflecting surfaces locks the two beams to a common frequency producing a dead band in the instrument. Efforts to improve mirrors as well as methods to circumvent lock-in via dithering or biasing have resulted in significant improvements in active ring laser gyro performance, but these devices have yet to reach the level of performance necessary to meet strategic mission requirements.

Multi-turn optical fiber laser gyros and PRRLGs, which are inherently not subject to lock-in, show the greatest promise of meeting strategic requirements while maintaining the other desirable features of ring laser gyros. These, however, are relatively immature devices and additional research in modeling and testing is required to obtain the required level of performance.

3.2. PROGRAM OBJECTIVES

The major objective of this effort was to obtain detailed mathematical models via experimental research of large area optical fiber laser gyros and PRRLGs. As a second objective, the devices that were built for this effort would be useful as geophysical gyros. Such devices are of interest to the Air Force Geophysics Lab (AFGL) and the Defense Mapping Agency Geodetic Survey Squadron (DMA GSS). Another purpose would be to use the superior PRRLG as a reference to test other less sensitive rotation sensors such as is required by the Central Inertial Guidance Test Facility (CIGTF). Furthermore, this PRRLG effort would have a desirable educational component to provide several stimulating research projects for USAF Academy faculty and cadets.

4. LASER GYRO CONCEPTS

Sagnac predicted that counter rotating beams in a ring interferometer would experience different path length changes if the interferometer was rotated. This path length difference would manifest itself in the form of a fringe shift, Δz, which he deduced to be:

$$\Delta z = \frac{4\vec{A}}{\lambda c} \cdot \vec{\Omega} \qquad (1)$$

where $\vec{A}$ is normal to the plane of the ring and is equal to the area enclosed by the ring, λ is the wavelength of the light, c is the speed of light and $\vec{\Omega}$ is the rotation rate vector. His apparatus consisted of an 866 cm^2

ring interferometer and a mercury arc lamp. Using the indigo line (0.44 μm) and rotating his apparatus at a differential rate of 4 rev/sec, he was able to observe the predicted fringe shift of about 0.07 fringe. Use of this concept as a practical gyro didn't catch on until about 1960, after the invention of the laser.

The first active ring laser gyroscope (Figure 1) was demonstrated in 1963. The ring was one meter square (1 m^2). As with Sagnac's device the basis of operation was a path length difference. However, with laser gain tubes as part of the ring, a path length change resulted in a shift in the laser oscillation frequency. A path length difference due to rotation produced a beat frequency Δf given by:

$$\Delta f = \frac{4A}{\lambda p} \cdot \Omega \qquad (2)$$

where P is the perimeter of the ring.[3,4]

Equations 1 and 2 show that Δf is larger than Δz by the factor $\frac{c}{p}$. This results in a much larger scale factor compared to Sagnac's device. There is, however, a problem with the active ring laser gyro that the Sagnac interferometer does not have. Backscattering off mirrors couples the two laser oscillation modes and when the Δf is small enough the two modes lock to a common frequency. Thus the active ring laser gyro has a deadband about zero rotation. Several solutions to this problem have been tried.

4.1. PRRLG APPROACH

FJSRL pursued a concept proposed by Ezekiel and Balsamo[5] (Figure 2). This approach is closer to Sagnac's method in that the light source is external to the interferometer ring. The difference being that the mercury arc lamp has been replaced by a laser. Having the laser external to the ring avoids the frequency lock-in problem. Through the use of acousto-optic modulators the change in effective path length is converted to an optical frequency difference which is identical to the beat frequency in the active ring laser gyro.

The counter rotating beams derive from a common single mode, single frequency laser. The "trick" is to keep both beams continuously resonant in the ring. The resonance condition for the clockwise (CW) beam is maintained via a path length control loop. A small amplitude high frequency dither on one mirror position provides the capability to determine the sign of the displacement error. Corrections to the path length to maintain maximum detector output are then made by moving another mirror. Both the dither and the correction movements are accomplished with piezoelectric translators (PZT).

Since the pathlength change due to rotation is of opposite sign for the two counter rotating beams, the correction for the CW beam only serves to worsen conditions for the counter-clockwise (CCW) beam. The resonance conditions which determine the detector output for the CCW beam is maintained by adjusting its wavelength via the acousto-optic modulator. The CCW detection scheme is the same as for the CW beam and a common dither serves well for both control loops.

The end result is that a rotation causes a path length correction for the CW beam and a wavelength correction for the CCW beam leading to a frequency difference between the two beams, which is proportional to the rotation rate (Equation 2).

The optical design problems with the PRRLG are challenging. The resonant ring is an open electro-magnetic waveguide whose dimensions are all large compared to the wavelength. It is a non-trivial problem to excite only a single mode in the ring. In general, several resonant modes will be excited by the incoming beam, despite the fact that the incoming beam itself is single mode. Ideally, only the fundamental transverse electromagnetic (TEM_{oo}) mode should be excited, but without taking precautions to match both the diameter and radius of curvature of the incoming beam to the resonator TEM_{oo} mode, higher order resonator modes will be excited. These higher order modes oscillate at different frequencies than the TEM_{oo} mode and thus cause a frequency pulling effect in the gyro. Several precautions must be taken to minimize the effects of these higher order modes:

(1) Match the incoming beam to the TEM_{oo} mode of the resonator.

(2) Design the resonator such that the most troublesome modes are far removed from the TEM_{oo} mode (in frequency).

(3) Place apertures in the ring to "kill off" the higher order modes.

(4) Align the mirrors and maintain this alignment.

A combination of all four of the above strategies is required.

Initial tests of a PRRLG set-up, as shown in Figure 2, with general purpose optical bench mounts, demonstrated the sensitivity of this concept to component and base instabilities. This preliminary experience was helpful in establishing a goal to construct a highly stable 0.62 m^2 system on a base which could be mounted on a precision, single-axis test table for calibration. This 0.62 m^2 feasibility demonstration model was to be followed by a much larger PRRLG, for greater resolution, to be mounted on the FJSRL isolation test pad (Iso-Pad). The Iso-Pad would provide seismic motion stability to the ring cavity and, as required, known rotation and tilt excitations for calibration. The concept in late 1982 was to construct a large, 37 m^2 ring above the false floor which covers all but the test piers of the Iso-Pad. As the conceptual design developed, the large PRRLG envelope was mounted on the Iso-Pad perimeter, below the false floor, which provided an area of about 60 m^2 (Figure 3).

4.2. THE 0.62 m^2 PRRLG

The 0.62 m^2 device was mounted on an Invar honeycomb base plate, which was attached to the face plate of a gas spin-bearing, gyro test table. The FJSRL Fecker gyro test table was mounted on an Iso-Pad test pier; this set-up provided both base stability and means of subjecting the PRRLG to known rotational rates. The Invar base plate was 122 cm square by six cm thick. The set-up was sensitive to high frequency vibrations associated with the test table and acoustic and air turbulent effects. These 'noise' sources were greatly reduced by adding a soft spring/damper mount (foam rubber) between the Fecker face plate and the Invar base plate, and a plexiglas cover over the optical system.

Figure 2 is representative of the 0.62 m^2 system concept. Key features were a low power, helium-neon laser source, a highly stable invar base, a non-evacuated resonator cavity, a high quality frequency synthesizer and lock-in amplifiers, and stable optical component mounts. Breadboard tests with commercial optical mounts showed that backlash and creep of as little as five arc seconds, completely deteriorated the cavity resonance conditions. Special mounts were designed by Major Shaw which were low profile, i.e., minimum height of optical center line to base, and had stiff, zero backlash, push-push adjustments. These were fabricated of 1020 steel and annealed after machining. The resulting mechanical stability of the opto-mechanical system was very good.

To support the 0.62 m^2 system effort, a computer program was developed which characterized the TEM_{00} mode of an arbitrary optical ring resonator. The program allowed for variation in the ring geometry as well as the mirror curvature. Thus it was useful for resonator design and aperture placement. Its primary use, however, was for mode matching. Given the specifications of the laser beam, the ring resonator and the mode matching optics, the program predicted how well matched the incoming beam was to the resonator TEM_{00} mode. It could further be used to check the sensitivity of the design to misalignments and other mechanical tolerances.

Another effort characterized the higher order modes in the resonant cavity. The main items of interest here were the resonant frequencies of the higher order modes and how energy coupled into those modes. A key result of mode matching analysis for the 0.62 m^2 device was selection of two 600 cm radius of curvature mirrors and two flat mirrors, based on the beam spot size and waist location.

Tests of the system were hampered by problems with the Fecker test table controls. It was not practical to obtain calibrated low angular rate excitations; at higher rate inputs, a resolution of about 3.5 ERU was obtained.

4.3. THE LARGE PRRLG CONCEPT

Both electrical and optical considerations for even a moderate size PRRLG are challenging, but the potential rewards of successfully building a very large device are enticing. The sensitivity to rotation increases with size; a square ring, 10 meters on a side, has a theoretical sensitivity of about 10^{-10} ERU (1.5×10^{-9} deg/hr) using a 4-watt frequency stabilized argon laser.[8] Such a device would provide a much better error model of the PRRLG than is currently available and also have the capability to investigate such effects as variability in the earth's spin rate and polar axis wobble. FJSRL has an isolation test pad facility that is seismically stable to better than 10^{-8} g and attitude stabilized to better than 0.001 arc seconds on which to build a 60 m^2 device.[9]

In order to measure fluctuations in earth rate with a precision of 10^{-9} ERU, extreme care must be taken to stabilize the normal to the ring with respect to the earth's rotation axis. The change in beat frequency due to a change in tilt α in the meridianal plane by an angle $\delta\alpha$ is

$$\delta\Delta f = \frac{4A}{\lambda p} \quad \Omega_E \cos(\Theta+\alpha)\ \delta\alpha \qquad (3)$$

where A is the area of the ring, Ω_E is the earth's rotation rate, P is the perimeter of the ring, λ is the wavelength of the laser output, and Θ is the latitude of the base location. Using the latitude at the Air Force Academy ($\Theta = 39^{\circ}\ 00'\ 24"$) and a $\delta\alpha$ of 0.001" arc seconds gives an input rate change of about 3.8×10^{-9} ERU. The actively controlled, inertially referenced, test platform (Iso-Pad) at the Frank J. Seiler Research Laboratory exhibits stability to 0.001 arc seconds RMS and has possibilities for some improvement at low frequencies.

The decision was made to make maximum use of the potential resolution from larger area obtained by constructing the large PRRLG resonator cavity on the Iso-Pad perimeter. The size of the ring, with optical axis 8.9 cm outside the sides of the Iso-Pad, was 60.8 m^2.

4.3.1. THE STABLE PLATFORM

The Iso-Pad is located at the U.S. Air Force Academy's Guidance and Control Laboratory, jointly operated by the Department of Astronautics and the Frank J. Seiler Research Laboratory. Figure 3 is a pictorial of the Iso-Pad, the bulk of which is housed below the main floor. Note the nine test piers, which are an integral part of the Iso-Pad, protruding through holes in the laboratory floor. These test piers are accessible for stable, vibration 'free', experiments such as 0.62 m^2 prototype PRRLG mounted on the gyro test table (Figure 3). The 'false' floor supports personnel and test equipment. The "sealed" 'inner' Iso-Pad area has separate air conditioning and air lock entry.

The Iso-Pad is constructed of steel reinforced concrete. Figure 3 shows main equipment items and construction features of the Iso-Pad. The Iso-Pad is 7.62 meters square with nine circular piers rising 0.76 meters up from the main block. The bottom of the block has a cruciform shape 1.37 meters high which accommodates the Iso-Pad location of the support system. The Iso-Pad is supported by 20 undamped pneumatic isolators, "actuators", and floated approximately 1.25 cm above the base slab. The base slab which supports the pneumatic isolators is of the seismic mass design, i.e., physically distinct from the concrete basement floor.

The Iso-Pad support is provided by the flow of pressurized air into 20 pneumatic actuators. The final report of the Iso-Pad provides a detailed description.[9]

4.3.2. RESONATOR STRUCTURE

An interferometer monitored the shape of the Iso-Pad. Results indicated angular deflections due to Iso-Pad structural bending and twist are less than five arc seconds. However, perimeter changes caused by temperature variations of 1^{o} C (the controlled tolerance) could be as long as 60 μ m. This is equivalent to about 100 wavelengths of the Argon laser. A two pronged approach for solving this problem was used in the large ring design.

The principle approach was to incorporate additional perimeter stiffness using a "zero" thermal coefficient coefficient material reference bar assembly to which all PRRLG optical components are attached. A back-up design approach was to develop a coarse path length controller for obtaining side and/or perimeter length stability through an active control system. This approach is described in the support projects section (Chapter 6).

Figures 3 thru 7 illustrate the large ring design concept. The glass ring vacuum envelope has its axis about nine cm outside the sides of the Iso-Pad (Figure 3). The glass ring structure (Figure 4) serves the primary function of maintaining a high vacuum for the two counter propagating beams. The corners are terminated at 25 cm (10 inch) stainless steel cubes which house the resonator corner mirrors. Initial operation of this ring would have all four corner cubes firmly affixed to the Iso-Pad. The ultimate configuration involves floating three of the corner cubes on platform air bearings and firmly attaching the fourth to the Iso-Pad. The floating cubes are referenced to the fixed cube via a tri-bar ZERODUR (a registered trademark of Schott Glaswerke, Mainz) structure (Figure 5). With $1^{o}C$ temperature control the 7.5718 m ZERODUR bars should remain within 0.4 μm of their nominal length. This requirement is driven primarily by the necessity for scale factor stability. Since earth rotation, $\Omega_E \sin \Theta_1$ is a given input the fractional stability in the scale factor must be better than one part in 10^{10} to achieve comparable earth rate sensitivity. For a PRRLG a uniform expansion or contraction of the perimeter will have no first order effect on scale factor, until it becomes necessary to jump a mode. Mode hopping can be sensed and adjustments made. For the $1^{o}C$ swing $\delta f \simeq$ 12 MHz. This will not require mode hopping. The displacement of one element (cavity mirror) with respect to the rest of the system, however, directly affects the scale factor of the device. A sensitivity analysis has been initiated to examine such deformations and their effect on system scale factor. One case examined is that in which one spherical cavity mirror is perturbed along one of the resonator optical axes. The result of such a perturbation is shown in Figure 6.

Another perturbation on cavity dimension is a variation in atmospheric pressure (since the cavity is evacuated). This gives an uniform dimensional change and based upon the cross-sectional area specified (35 mm^2) for the support rods and Young's Modulus (E = 91000 newtons/mm^2) of the ZERODUR material, this should be a tolerable error source. However, if pressure variations prove to be an intolerable error source, the various techniques are available to compensate for this error.

4.4. STABLE LASER

The large ring cavity linewidth is anticipated to be $\sim$300 Hz (cavity finesse between 30,000 and 60,000). In lieu of path length control on the large resonator, the laser source will be locked to the resonance of the large ring cavity. The fundamental mode of the ring resonator must be excited with sufficient signal to allow the high gain servo loops to create and hold a "hard" lock on the ring resonance. To achieve the intermediate level of laser frequency stability necessary to accomplish this the laser may first be locked to a smaller, passively stable cavity. An experiment was performed to employ this scheme using a 30,000 finesse, 52 cm perimeter ZERODUR passive resonant ring cavity (on loan from Rockwell International). This technique is being employed by Dr. J.L. Hall, at the National Bureau of Standards, to frequency stabilize a 4-watt Argon laser to be used on our large PRRLG. Conservative estimates for the expected performance of the stabilized laser are:

a.	Laser spectral linewidth	< 3 kHz
b.	Laser output power	> 400 mW @ 514.5 nm
c.	Beam pointing stability (with fiber-optic output coupler)	< 50 radian per degree C
d.	Temperature coefficient	$< 10^{-9}$ per degree C
e.	Long term (one year) frequency stability	$< 10^{-7}$

This "pre-stabilized" laser energy would then be coupled into the large ring cavity via the input optics loop which contains the phase/frequency modulators necessary for the final lock to the large ring resonance.

The scale factor for this device is such that the beat frequency between counter-propagating fundamental modes will be about 700 Hz due to the sin Θ_1 (latitude) component of earth rotation rate (Ω_E) "seen" by the instrument. To measure changes in effective earth rotation rate of parts in 10^{10}, the instrument must detect variations of 10's of nanohertz in this nominal 700 Hz beat. This requires the final frequency control loops to be stable against drift and bias shifts (i.e., 1/f noise) to this same level of precision. At the time of program termination these questions of system electro-optic, acousto-optic, electronic and mechanical stability were being addressed by in-house work and through funded efforts with Dr. Dana Anderson and Dr. John Hall.

The anticipated configuration for control loops is basically that reported by Sanders, Prentiss and Ezekiel,[10] with the path length control replaced by laser frequency control and additionally using the reflected beam from the input mirror of the large ring cavity for higher bandwidth. This latter modification is required since the cavity storage (ring-down) time is expected to be on the order of a milli-second.

5. CLOSE-OUT STATUS

The fabrication and installation of components to the large ring was progressing toward the configuration as shown in Figure 4. Initial operation of the large PRRLG was to rely on the Iso-Pad's structural stability and the evacuated (10^{-7} TORR) glass envelope for short term tests of the system before installation of the ZERODUR, "zero" coefficient of thermal expansion, reference tri-bar assembly (Figure 5). The temporary mounting brackets could be removed and the tri-bar system added without major disassembly.

The Iso-Pad and actuator columns have been cut away and the 254 mm cube bell jars installed (Figures 7 and 8). Vibration tests of the bell jar mounting brackets, fabrication of the glass envelope sections, and fabrication of temporary envelope mounts (without the ZERODUR reference bar provision) are complete. The two vacuum systems, consisting of venturi, adsorption, and vac-ion pumps, and a leak detector/mass spectrometer, are on hand. The ring was partially assembled, each side was to have been leak tested and verified before proceeding to the next side of the ring. Figure 7 shows two sides of the ring from the southwest corner and Figure 8 shows the assembly detail of the southeast cube bell jar with attached glass envelope. The glass envelope uses stainless steel-to-glass adapters and vac-u-flat couplings, with flexible bellows at each of the cube faces. The 182 newton evacuation force requires that restraining brackets hold the cubes in place until the ZERODUR stabilizer system is installed. The ZERODUR tri-bar assembly of 35 mm square x 1.893 m long bars, twelve bars per side, (four sets of three) will contact and reference the cube locations. The ZERODUR bars were being purchased, and a contract was in progress for a research hydrostatic air bearing to effect a "zero" friction mount for the 890 newton (200 pound) bell jars.

Several areas were under investigation at the time of program termination. Candidate designs for the bell jar mounts which would free the corner cubes from the expansion motion of the Iso-Pad were being analyzed. The optical-mechanical hardware to input the laser to the ring was being designed. Investigations were being conducted to insure against ZERODUR bar buckling caused by the ring evacuation and to verify ZERODUR physical properties which are key to this application (e.g., compressibility resulting from the usual 40 mm Hg variation in barometric pressure at this location). A MASSCOMP data acquisition system was purchased and an uninterruptable power system for long term test and data processing was being considered. Verification of the digital mode control measurement servo and reactivation and improvement of the Iso-Pad active controls had begun. Preliminary studies of the various geophysical effects which would influence the large ring output were also being conducted.

Existing program plans called for a significant increase in the current level of effort to complete the design and fabrication of the large PRRLG system. The program plan called for expanded support by contractor personnel, in particular by the University of Colorado. Completion and initial operation of the preliminary ring system (evacuated glass tube - helium-neon laser) was projected for late 1986. The final system configuration was scheduled for completion and initial operation in the fall of 1988.

6. SUPPORT PROJECTS

6.1. GENERAL

This section briefly describes the many short-term projects which contributed to the project. These support projects, including experimental and analysis tasks, were performed by FJSRL staff, university faculty and students, AFIT students, and USAF Academy faculty and cadets. Most of these projects resulted in USAF technical reports, presentations, or graduate theses. Appendix A lists all such work unit related documentation.

6.2. OPERATION STALACTITE

This was a combination research and education project. The objectives for the students were to give them an idea of how a research and development contract is directed, to exercise their design ability and to motivate them positively toward engineering research. The instructors objectives were to acquire first-hand insight and experience with a frequency stabilization technique and to obtain ideas of how to modify the passive ring resonator gyroscope design in order to obtain better performance. The concept was to have the students act as a team (although each had his own responsibilities) to design and build a frequency stabilized helium-neon laser under the supervision and direction of the instructors. The approach was to use the frequency stabilization techniques developed at the Joint Institute for Laboratory Astrophysics (JILA) at the University of Colorado at Boulder.

Contributors included the instructors: Lt Colonel T.T. Saito, Major G.L. Shaw, and Major J.J. Pollard. The cadets were L.P. Conley, C.F. Calamoneri, K. Anders, M.A. Lorenz, J. Diehl, S. Reynoso, and T. Poole.

The students gained significant understanding into requirements and methods of executing research and development. They obtained a laser frequency stability better than 10 MHz.

The project was successful. The students were able to apply their previously acquired knowledge to overcome hurdles and in the process they became highly motivated toward engineering research.

6.3. FECKER GYRO TEST TABLE CONTROL

The Fecker gyro test table was used as a mounting base of the 0.62 m^2 PRRLG. The Fecker table is capable of subjecting the system under test to prescribed orientations and angular rates. The obsolete control electronics had malfunctioned and new controls were required.

The refurbishment of the Fecker gyro test table was a significant problem. The adopted approach required several new circuits to implement table control from a Z-80A microcomputer.

The investigators involved were Major J.J. Pollard, SMSgt E. Barr, Lt S. Kale, Lt G. Richter, Ms. N. Sunnaa, Mr. J. Walters and Sgt P.K. Earl.

The resulting controls, as of completion in 1982, were satisfactory; later, when attempts were made to effect very low angular rates, performance had degraded. Additional work will be required before the Fecker table is again operable.

6.4. PRRLG DATA PROCESSING

The PRRLG would require collection of many analog and digital signals for transmission to the VAX 11/780 computer for analyses. The approach taken which offered the most versatility was to use instruments which were compatible with the HPIB industry standard and develop a compatible network processor. The FJSRL developed Z-80A microcomputer system was applied to the task.

Personnel initially developing the system were Major J.J. Pollard, Sgt P.K. Earl and SMSgt E.L. Barr.

The available test equipment and new off-the-shelf component based processor system were satisfactorily applied by Captain D. Fredal and MSgt P.G. Swann to several similar applications. More recently, a new MASSCOMP data acquisition system featuring high speed processing and A-D/D-A capability was purchased to provide the large PRRLG with stand-alone capability.

6.5. PRECISION MODELLING OF THE ISO-PAD

Dimensional variations of the base for the PRRLG on the order of a wavelength would be of concern. Obtaining a square resonant cavity within one mm requires very accurate measurement of the Iso-Pad included angles. Two interferometers, a HP 5526A and a Teletrac TIPS, and a MicroRadian autocollomator were procurred for this purpose. Measurements were made of variations in the Iso-Pad flexure perimeter, length of a side and included angle. Analyses were made of ring dimensional and shape effects on PRRLG scale factor and performance.

The objectives of these tests were to model Iso-Pad dimensions and variations to accuracies compatible with requirements of a 10^{-10} ERU PRRLG.

The investigators were Mr. B.J. Simmons, Major G.L. Shaw, Major G.T. Kroncke, Mr. L.L. Nelson, Lt L. Simcik, and Sgt P.K. Earl.

The important ring requirements established by experiment and analysis were sides equal to within one mm and mirror orientation to within five arc seconds; also, post alignment variations in corner mirror position to within one or two wavelengths were desired to limit piezoelectric transducer (PZT) mirror actuator range requirements. Iso-Pad measurements indicated satisfactory stability on included angles and structural bending; however, length of side variations were of the order of 15 μm. These results established criteria for the two approaches to obtaining ring stability, the ZERODUR reference structure and the back-up coarse path length controller.

There was also a review of modal analysis of the Iso-Pad structure and analysis to determine optimum mounting of the ring to the Iso-Pad toward obtaining minimum coupling of Iso-Pad residual vibration to the ring.

6.6. COARSE PATH LENGTH CONTROLLER

The objective of the coarse path length controller was to determine the feasibility of an active position control system as a technique for maintaining the large ring dimensions to within 0.5 μm. The feasibility test selected was to actively control the perimeter established by three mirrors and the Hewlett-Packard interferometer mounted on the four corners of the Iso-Pad. The optical components were rigidly mounted to the Iso-Pad; thus a long term variation in this perimeter on the order of 50 μm could be expected. As a worst case, this ring was not set up in a vacuum envelope, and due to air density variations, an apparent dimensional change in the perimeter was 500 μm.

The approach to the system design was to use the interferometer to measure perimeter variations, convert the digital output to analog error signals, amplify and compensate these signals to drive an inchworm PZT translator which controlled the position of one of the perimeter mirrors.

The investigators on this project were Mr. B.J. Simmons, Mr. J. Keating, Major J.J. Pollard, and Lt G. Richter.

The results were demonstrated by a three-day operational test. The peak variations in the optical perimeter were +0.1 to -0.23 μm, with an rms error of 0.05 μm.

6.7. MODE MATCHING A PRRLG

This effort was part of the 0.62 m^2 PRRLG project, a forerunner to the much larger 60 m^2 PRRLG. The objective was to eliminate false rotation indication in the ring by maximizing the energy in the TEM_{oo} mode thereby reducing the intensity of the higher order resonance modes. The concept was to locate and place mode matching lenses in the incoming beam path in order that the incoming beam match the resonator beam TEM_{oo} mode at the input mirror.

The investigators were Major G.L. Shaw, Lt Col T.T. Saito, Major T.D. Baxter, Captain R.A. Motes, Lt Col R.T. Evans, Major G.T. Kroncke, Lt J. Gossner, and Mr. J.D. Keating.

The higher order modes were reduced and in some cases eliminated, and simultaneously the intensity of the fundamental mode was enhanced. With mode matching, the ratio of the TEM_{oo} to the higher order modes was improved by a factor of 12. Mode matching in the horizontal and vertical planes was demonstrated to be an effective method for enhancing the TEM_{oo} mode relative to higher modes.

6.8. THE TWO LASER PRRLG

The objective of this project was to develop a PRRLG utilizing two lasers. Two conditions were sought: the isolation of the resonant cavity from external noise and improved performance of the gyroscope. The concept was to phase lock both lasers to an evacuated resonant cavity.

The investigators were Mr. M.K. Hinckley and Major G.L. Shaw.

The characteristics of the laser beam were measured and following mode matching the cavity was locked to the laser. In a second experiment the laser was locked to the cavity.

6.9. SEMICONDUCTOR LASER SOURCE FOR PRRLG

This project investigated methods to frequency stabilize semiconductor lasers to make them compatible for use with a high finesse ring cavity designed for 0.83 μ m. Reduced cost, greater reliability, and compatibility with integrated optics are some of the advantages gained by incorporating semiconductor lasers into the design of PRRLGs. Unfortunately the large spectral linewidth typical of semiconductor lasers greatly limits the sensitivity of such a configuration. This project detailed the modification of a laser diode to obtain a stable, single mode, narrow spectral output.

The principal investigators were Captain D.J. Stech, Major G.L. Shaw, Major J.R. Rotge', Mr. L. Pedrotti, and Dr. J.L. Hall.

Optical feedback was investigated to obtain spectral narrowing of the laser diode. An optical feedback configuration compatible with the input optics to a PRRLG was designed. Spectral narrowing and modal dynamics of the external coupled cavity laser were measured. By temperature stabilization and optical feedback a free running linewidth of 60 MHz was reduced to below 13 MHz and was maintained in a single mode for 20 minutes or more.

6.10. EFFECTS OF ACOUSTO-OPTIC MODULATORS ON LASER GYROSCOPES

The purpose of this project was to evaluate potential error sources which were associated with the acousto-optic modulators. Four potential errors were examined: angular deviation of the beam, horizontal and vertical beam profiles and temperature sensitivity. Beam directional deviations were measured for various input frequencies from nine different acousto-optic modulators. Using the measured deviation the change in mirror reflectivity was calculated. Beam profiles for various frequencies of the acousto-optic modulator were measured. The sensitivity of the beam deviation to temperatures over a 100° C span were evaluated.

The investigators were Captain E.M. Walling, Major G.L. Shaw, and Lt Colonel T.T. Saito.

The angular deviation of the beam due to the acousto-optic modulator was measured and found to be in agreement ($\sim$ 1%) with the manufacturer's specification. The cavity mirror reflectivity change due to this deviation was found to be such that it may affect gyroscope operation. The modulators are insensitive (to the level of measurement possible) to temperature variations around room temperature. The beam horizontal and vertical profiles were all Gaussian with one exception.

It was concluded that further investigation is needed on the effect of beam deflection and mirror reflectivity for the PRRLG. Also, the horizontal and vertical beam profiles for the modulators should be checked before they are used.

6.11. ISO-PAD STABILIZATION IMPROVEMENT

Under normal operating conditions the Iso-Pad has a stability of 10^{-3} arc seconds in tilt for disturbances from zero to 0.1 Hz. Accelerations are controlled to a level of about 10^{-8} g from 0.1 to 20 Hz. There are deficiencies in the robust controls from 0.2 to 0.4 and above 15 Hz. As the base for the 10^{-10} ERU PRRLG, this performance is marginal. The objective of this task was to investigate means of correcting these deficiencies.

The approach to the 'low' frequency improvement involved adding higher flow pneumatic boosters to improve response in the 0.2 to 0.4 Hz band and add appropriate lead compensation. High frequency improvement was attempted with a new lead/lag compensator.

The investigators were Mr. L.L. Nelson, E-6/OT A.P. Hardy, and Mr. B.J. Simmons.

Some improvement was obtained in both frequency bands. The high flow air boosters have been added to all pneumatic servo channels. They will require precise tuning before full servo activation. The high frequency improvement was demonstrated in one channel but it has not been incorporated in all four high frequency channels.

6.12. PRRLG INFRARED COMPONENTS

A hybrid system utilizing the advantages of the passive ring resonator and the micro-optic gyro was proposed and some components studied experimentally for the infrared region.

The evaluation and development of components for an infrared passive laser gyro had two main objectives. These were the experimental evaluation of the feasibility of the hybrid gyro concept and the development of optical components, specifically a polarization modulator, for the combined new system. The characteristics of the elements of the hybrid gyro were analyzed and potential problems were identified.

The investigators were Dr. D.Y. Chung and Major G.L. Shaw.

An experiment was designed to build and test a fiber optic polarization modulator. The fiber optic polarization modulator was successful, achieving polarization modulation up to 200 Hz.

6.13. UNIVERSITY OF NEW MEXICO ANALYSES

Researchers associated with the University of New Mexico performed analyses and experimental support in special problem areas associated with the PRRLG and optical rotation sensors in general. A further objective of this effort was to develop theory, analyze quantum detection limits and investigate enhanced performance by non-linear optical methods.

Investigators were Dr. M.O. Scully, Dr. J. Kim and Mr. L. Pedrotti. It was planned that other visiting professors and graduate students would support the project.

Analysis by Dr. Scully and others showed the potential for relativity experiments and gravity wave detection by an optical rotation sensor of the resolution projected for the PRRLG.

Additional analyses by L. Pedrotti included shot noise, minimum error signal, mechanical vibration effects, and beam spectral broadening. Expressions were developed for the signal intensity at the detectors, and for several signal-to-noise deteriorating effects. These equations are the basis for electronics performance specifications, mechanical stability requirements, optical component characteristics, and trouble-shooting techniques.

Quantum noise levels in the passive ring were investigated. Design considerations for the large PRRLG were proposed based on this work.

6.14. EVALUATION OF TWO PRRLG DESIGN CONCEPTS

One objective of this research was to compare the performance of two design concepts of the passive ring laser gyro. A second objective was to maximize the rotation rate sensitivity in either design to achieve the sensitivity level of 0.001 ERU. The two concepts involved different methods of monitoring the cavity power. One method monitored the power transmitted through the cavity to keep the two cavity beams in resonance. The other method monitored the power reflected from the cavity. The gyro rotational rate sensitivity was used to compare the two designs.

The investigators were Captain M. Nelson, Major S.R. Balsamo, Major G.L. Shaw, and Lt F. Rand.

The two concepts were built using the same resonant cavity, and tested in the areas of alignment and performance. The concept which monitored the reflected power was about three times as sensitive as the other concept. Using a 100 second integration time the noise equivalent rotation of the reflected power design was about 0.004 ERU, which approaches the performance attained with active ring laser gyros.

6.15. NOISE ANALYSIS

AFOSR funded a program on basic noise analysis of ring laser gyros at Oklahoma State University.

This effort identified and characterized noise sources (e.g., laser frequency fluctuations), quantum noise, flicker noise and apparatus dependent terms such as random walk.

The investigators were Dr. H. Bilger and graduate students from Oklahoma State University.

6.16. PRRLG CALIBRATION

Two methods of producing test signals of known magnitude were investigated as to their potential for calibrating the large PRRLG: 1) tilting the base of the ring by a known angle, and 2) utilizing Fresnel drag from a controlled flow of gas in the resonant cavity. Known tilts which change the effective component of earth rate can be obtained by rotating the Iso-Pad about the east-west axis. A Fresnel drag effect is obtained by injecting known gas flow into the PRRLG cavity. Analyses of these possibilities were performed.

The investigators were Dr. H. Bilger, Major G.L. Shaw, and Mr. B.J. Simmons.

Models were derived for providing known effective rotational rate signals from tilt, time varying tilt, and adjustable gas leaks. Calibration methods based upon these effects were to be incorporated into the operation and checkout procedures for the large PRRLG.

6.17. A LASER FEEDBACK CONTROL DESIGN FOR PRRLG IN A VERY HIGH FINESSE CAVITY

High finesse resonant cavities proposed for use in large PRRLGs exhibit linewidths significantly narrower than commercially available frequency stabilized lasers. This can limit the performance due to a decreased signal-to-noise ratio. The purpose of this research was to construct a unique design to reduce linewidth of a helium-neon laser by frequency locking the laser to a 25,000 finesse, 169 cm^2, resonant cavity. A resulting random error of 0.0078 ERU was achieved for an averaging time of 10 seconds. Extrapolation of the performance to the large PRRLG indicates that sensitivities required for precision rate sensor testing and general relativity experiments are attainable.

This level of sensitivity will only be possible through the use of high finesse cavities. Since the linewidths of these high finesse cavities are narrower than commercially available lasers, techniques are required to match the laser linewidth to that of the (high finesse) cavity. Historically, the method used to achieve this has been to lock the resonant frequency of the cavity to that of the laser; that is, changing the resonant frequency of the cavity by controlling the path length and thus matching the cavity resonant frequency to the laser frequency. This method is limited by the bandwidth of the PZTs which are used to control the cavity dimensions. This research took the alternate approach of locking the laser frequency to the cavity resonant frequency. Since the process of controlling the laser frequency by regulating injection current has a higher bandwidth than controlling the cavity dimensions via PZTs, a more precise lock is obtainable.

The principal investigators were Captain M.A. Lorenz, Major G.L. Shaw, Major J.R. Rotge', and Dr. J.L. Hall.

Results achieved with this new technique were encouraging. A helium-neon laser was locked to a 25,000 finesse cavity. Although the cavity lifetime limited the bandwidth of the controller, it was not a driving factor at that finesse.

7. ACCOMPLISHMENTS, CONCLUSIONS AND RECOMMENDATIONS

7.1. ACCOMPLISHMENTS

The accomplishments of the Optical Rotation Sensor project were many. Over 17 related research and development tasks were completed. FJSRL established a very good working relationship with the electro-optics community and many USAF Academy cadets and faculty benefited from their experiences with these research endeavors. The feasibility of developing a large, ultra-precision, rotation sensor was demonstrated. Scientists in several fields including astrophysics, general relativistic physics, geophysics, and inertial sensing/navigation were enamored with the possibility of a solution to their particular sensor problems. Much of the error analyses, design, and equipment procurement were completed toward fabrication of an experimental rotation sensor extending the state-of-the-art by three to four orders of magnitude.

7.2. CONCLUSION

While significant manpower and funding are required for completion of a 60 m^2 PRRLG, no insurmountable problem requiring a scientific breakthrough has been identified.

7.3. RECOMMENDATIONS

There is a requirement for improving the state-of-the-art in inertial rotation sensors. Therefore, it is recommended that FJSRL and AFOSR be alert to requirements developing within the Air Force Strategic Defense Initiative Organization, Inertial Guidance Test Facility and Air Force Geophysics Laboratory areas of responsibility, and that a PRRLG project be considered for reactivation.

8. ACKNOWLEDGEMENTS

The authors would like to acknowledge Major Gerald L. Shaw for directing the Optical Rotation Sensors project and for managing the many support and participating efforts that made this such a successful program and bringing FJSRL international recognition.

Also, we express our gratitude to the many participants who have helped make this a successful program of significant scientific merit. At risk of unintentional omission, we extend to the following people our gratitude and share regrets that the project was not completed.

Colonel James E. Baker, Colonel William Siuru, Colonel Hugo Weichel, Lt Colonel Dan Biezad, Lt Colonel Nickolas Belmonte, Lt Colonel Bob Dunn, Lt Colonel Richard T. Evans, Lt Colonel John H. Pletcher, Lt Colonel Theodore T. Saito, and Lt Colonel Kenneth E. Siegenthaler.

Major Albert J. Alexander, Major Craig Baer, Major Salvatore R. Balsamo, Major T. Dale Baxter, Major Gary Butson, Major Bruce Harmon, Major Joseph J. Pollard, Major Gerald L. Shaw, Major Felix Morgan, and Major Paul Torrey.

Captain Dan Fredal, Captain Dan Herrick, Captain James D. Ledbetter, Captain Mark Lorenz, Captain R. Andy Motes, Captain Mark Nelson, and Captain Eileen Walling.

Lt Dan Brett, Lt Steve Brown, Lt Terry Fundak, Lt Steve Kale, Lt Carl Kushner, Lt David Legate, Lt Tim Poole, Lt Frank Rand, Lt Gary Richter and Lt Luke Simcik.

MSgt Earl L. Barr, MSgt Paul G. Swann, TSgt John Nelson, SSgt Andrew Hardy, Sgt Pamela K. Earl, and AlC Thomas A. Dunlap.

Dr. Dana Anderson, Dr. Hans R. Bilger, Dr. David Chung, Dr. Daniel DeBra, Dr. John O. Dimmock, Dr. Ron Drever, Dr. Harry W. Emrick, Dr. Shaoul Ezekiel, Dr. John Hall, Dr. Franz Herkt, Dr. J. Kim, Dr. Tony Lawrence, Dr. Andrew Lazarewicz, Dr. Virgil E. Sanders, Dr. Howard Schlossberg, Dr. Marlin O. Scully and Dr. H. John Shaw.

Mr. Dick Alexander, Mr. Ray Allen, Mr. Charles Bowles, Mr. Dale Brown, Mr. Dave Cocolei, Mr. Bob Cooke, Mr. Bob Cooksey, Mr. Gene Dahl, Mr. Don Eckhardt, Mr. Al Freeman, Mr. Carl Geddes, Mr. Jim Hammond, Mr. Bob J. Hatfield, Mr. Stephen Helfant, Mr. Mike Hinckley, Mr. John Keating, Mr. Fred Kibler, Mr. Jim Matthews, Mr. Emory Moore, Mr. Larry L. Nelson, Mr. Joseph Ortiz, Mr. Leno Pedrotti, Mr. Hans Peters, Mr. Steve Renoso, Mr. Tom Rooney, Ms. Nisreen Sunnaa, Mr. Eric Udd, Mr. Tim Valle, Mr. Ray Voehl, Mr. John Walters, Mr. George West, and Mr. Howard Williams.

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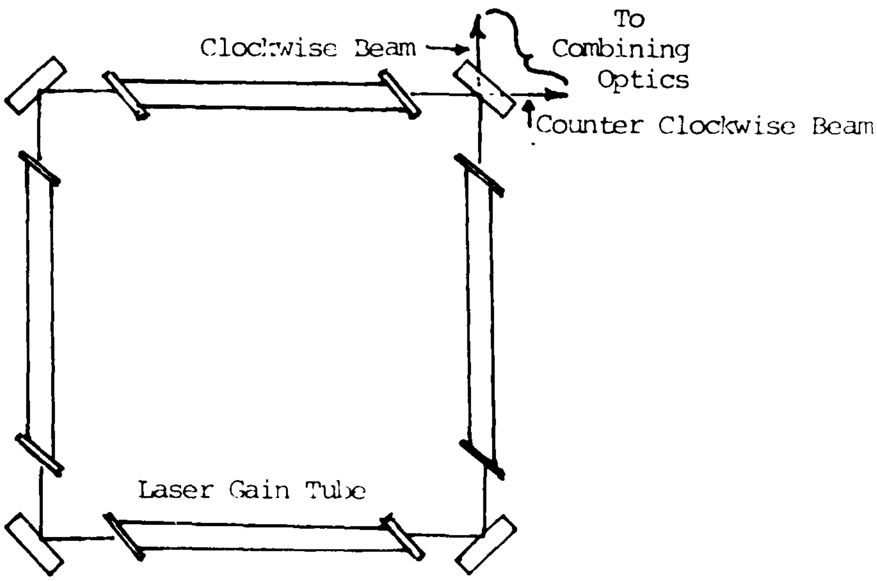


Figure 1. The First Ring Laser Gyro

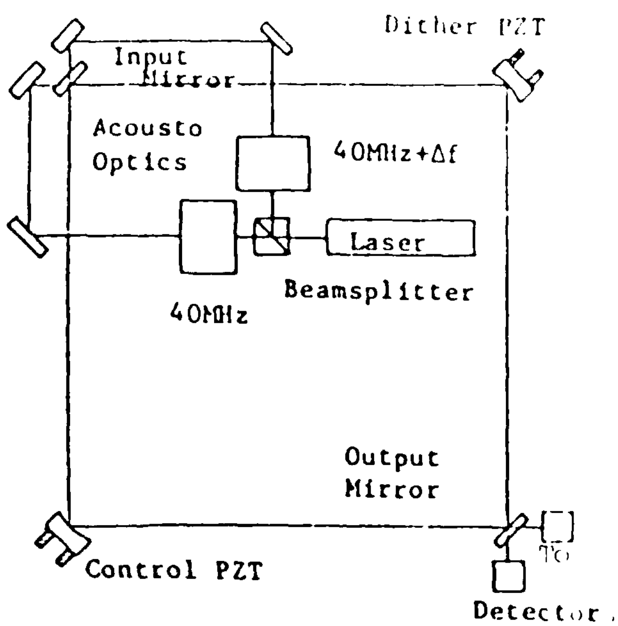


Figure 2. The Ezekiel-Balsamo Passive Laser

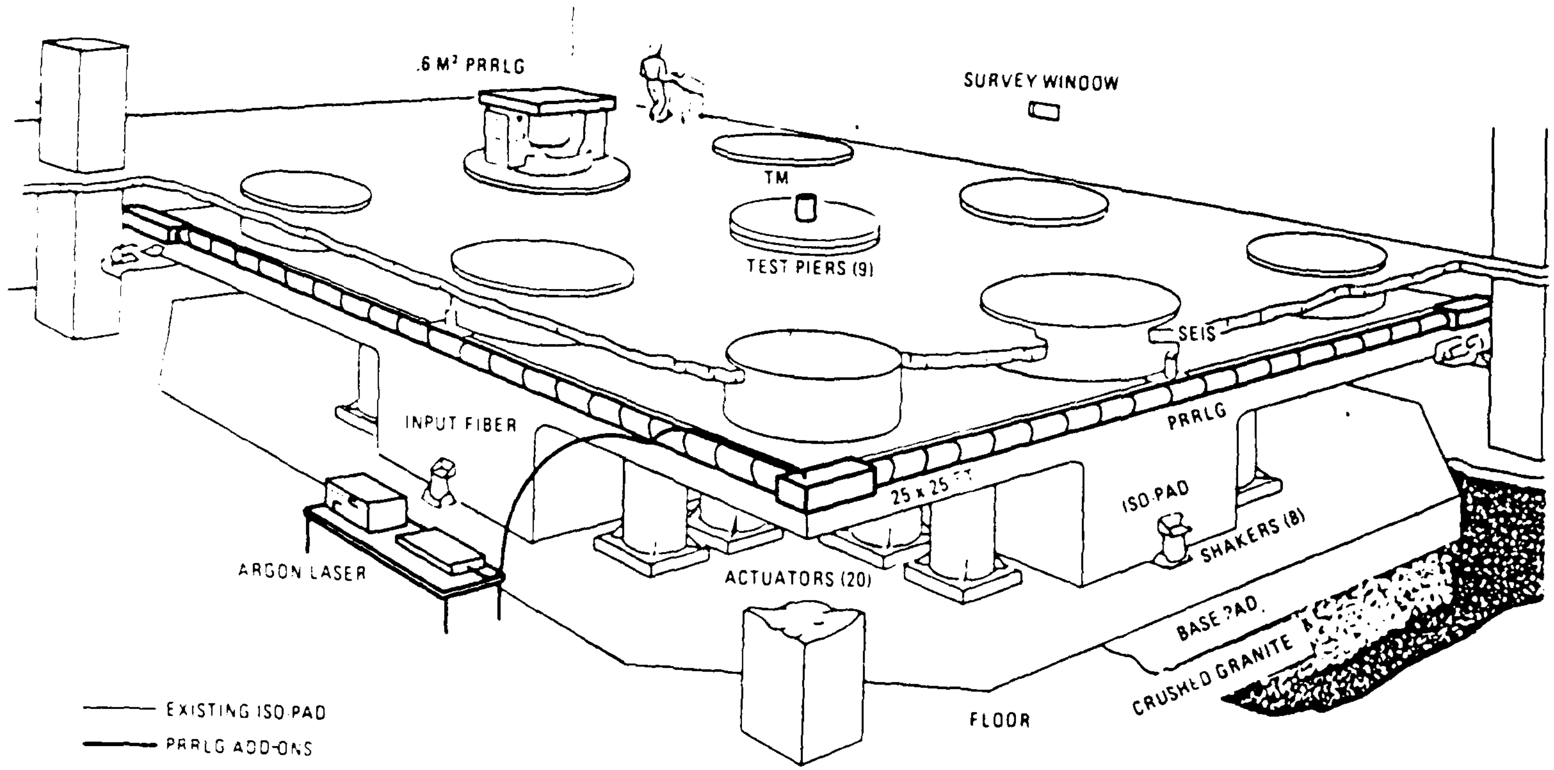


Figure 3. Large PRRLG on Iso-Pad

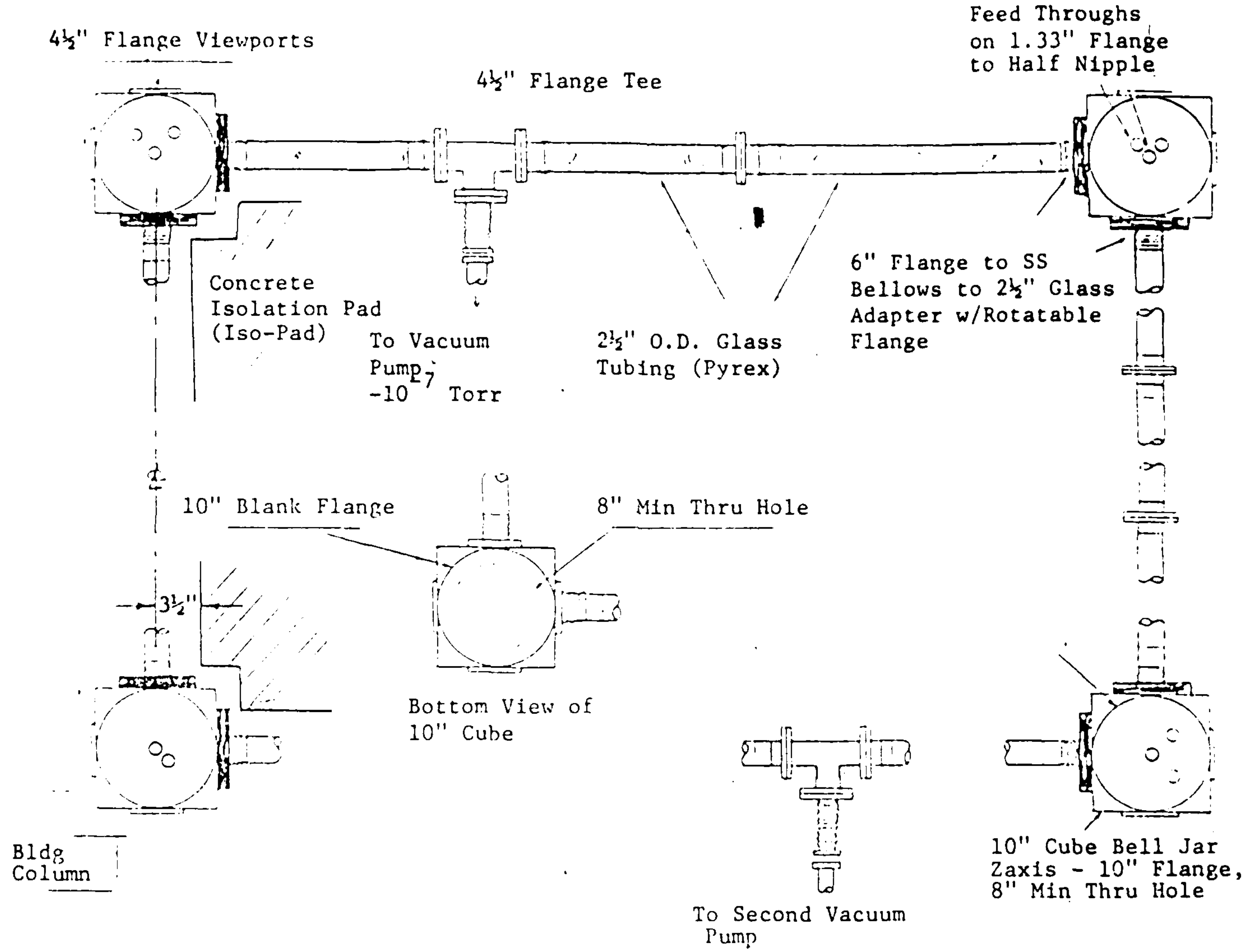
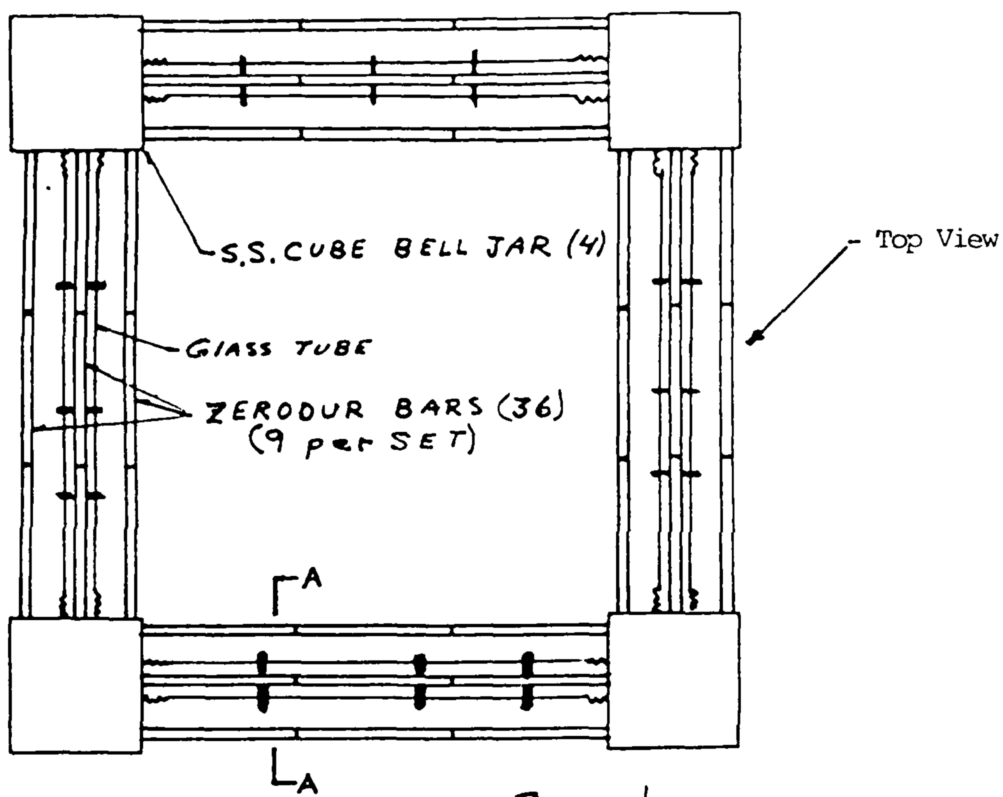


Figure 4. The Glass Ring Structure



TRI-BAR NOMENCLATURE

a- Bar Segment
a+b+c = Bar Assembly (f)
d- Tri-bar support bracket
e- Glass envelope
Tri-bar set- the three bar assy's f, g, & h

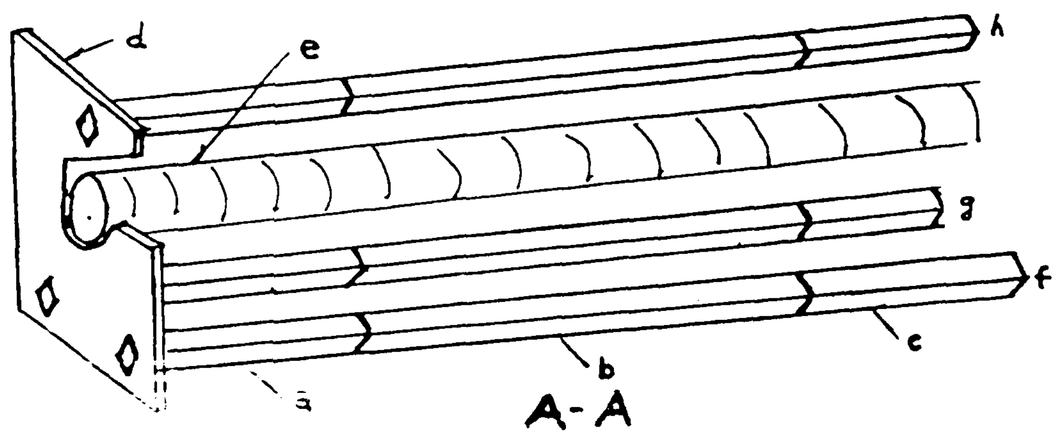


Figure 5. The ZERODUR* Tri-Bar Structure

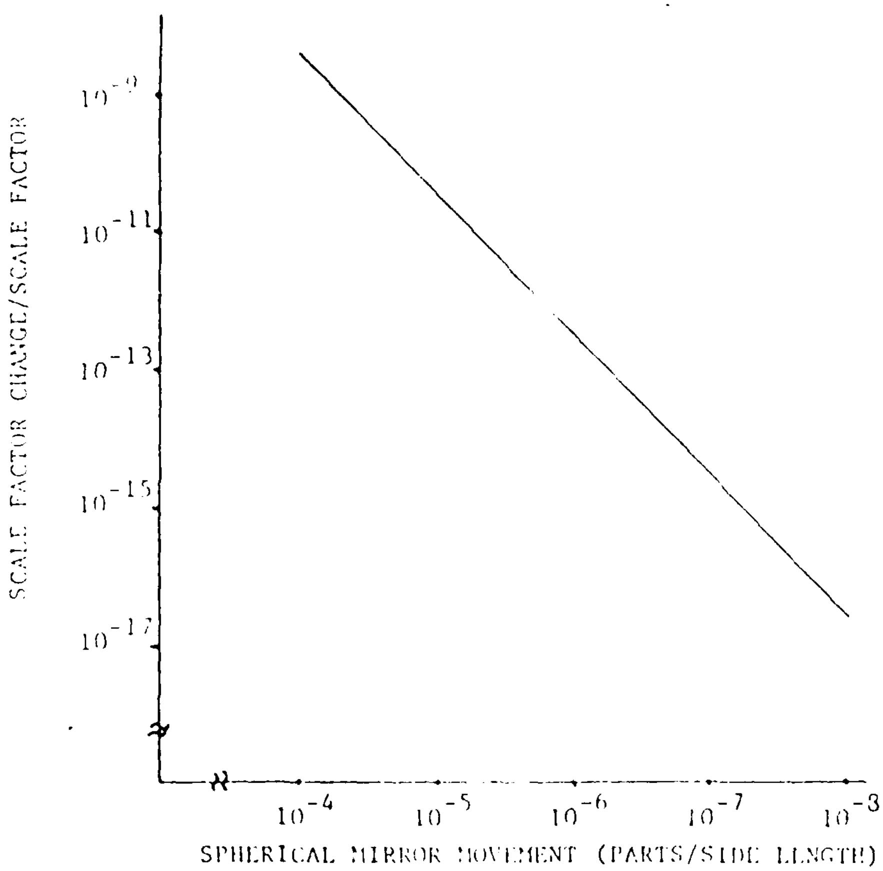


Figure 6. Scale Factor Sensitivity to Mirror Displacement

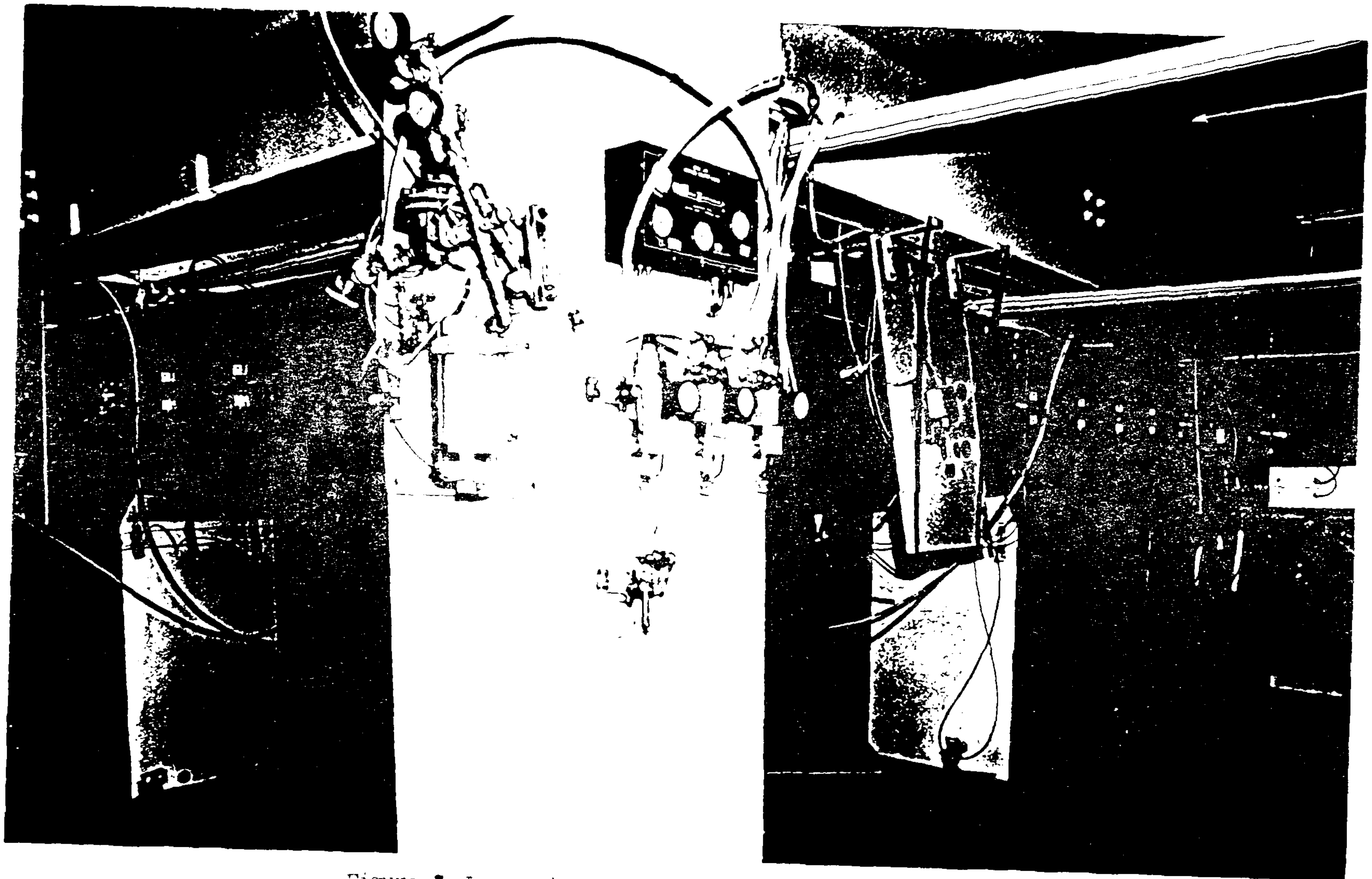


Figure 7. Large Ring on Iso-Pad (S.W. Corner)

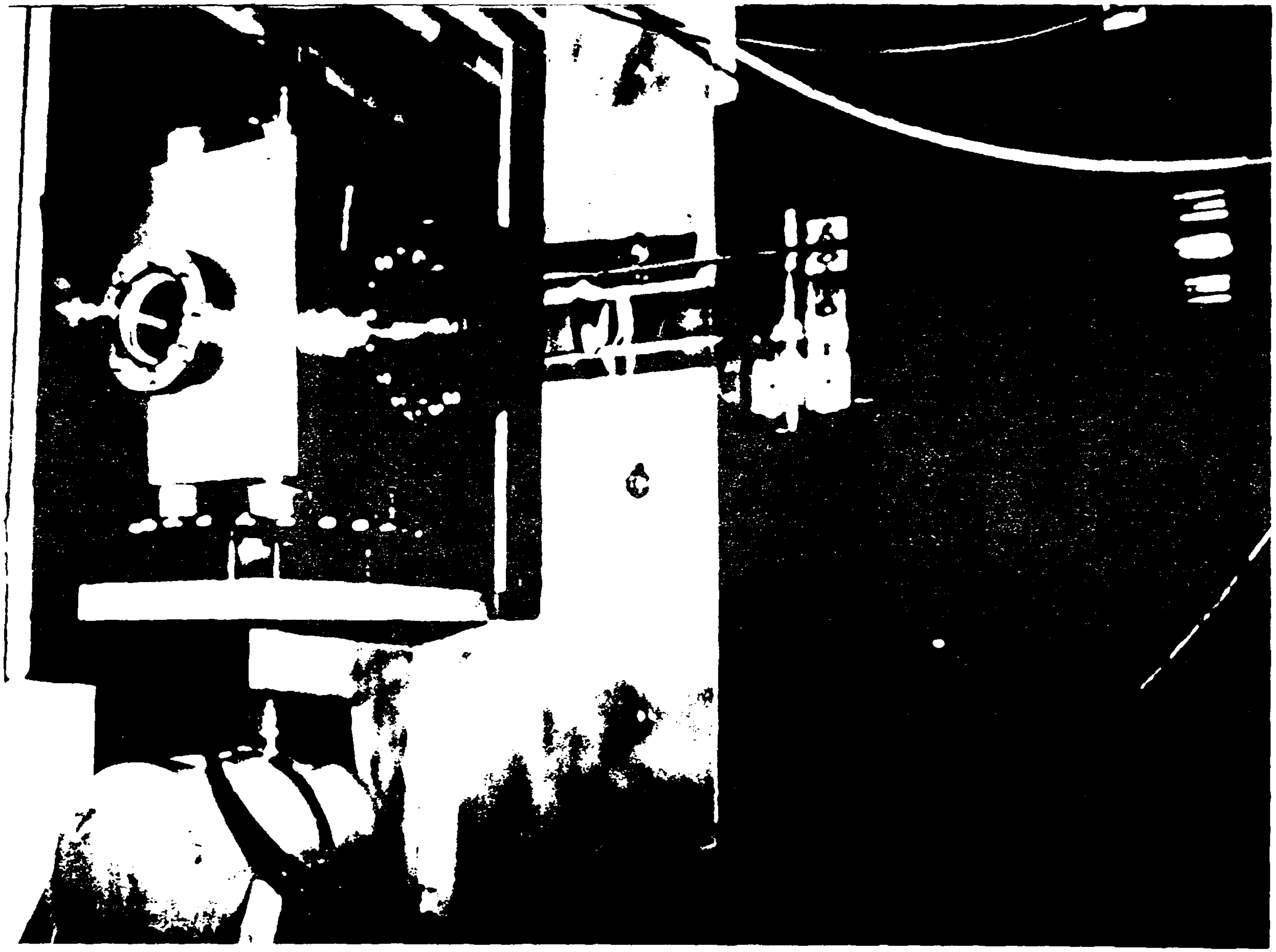


Figure 8. S.E. Cube Bell Jar/Glass Envelope Assembly Detail

APPENDIX

PRESENTATION/PUBLICATION LIST

FJSRL-TM-81-0005, "Operation Stalactite: Frequency Stabilizing a Helium Neon Laser -- A Cadet Design Project," by Lt's L. Conley, K. Anders, C. Calomoneri, J. Diehl, M. Lorenz, and T. Poole, Sep 81.

FJSRL-TM-82-0005, "FJSRL Z-80A Black and White Video Generator," Major J. Pollard, MSgt, Earl Barr, May 82.

FJSRL-TM-82-0006, "Expandable Single Board Microcomputer," Major J. Pollard, Lt S. Kale, Lt G. Richter, MSgt E. Barr, Jul 82.

FJSRL-TM-82-0008, "A Single Chip Microprocessor Controlled 8 Channel Data Acquisition System," Maj J. Pollard and Ms Nisreen Sunnaa, Jul 82.

FJSRL-TM-82-0009, "A Computer Interface for the FJSRL Fecker Gyro Test Table," by Maj J. Pollard, Lt S. Kale, Lt G. Richter, and MSgt E. Barr, Jul 82.

FJSRL-TM-82-0011, "Programs to Locate and Describe the Mode Matching Lenses for the PRRLG," by Mr. J.D. Keating and Captain G.L. Shaw, Aug 82.

FJSRL-TM-82-0017, "Design of a High Voltage PZT Driver," by Maj J. Pollard, MSgt E. Barr, and Mr. J. Walters, Sep 82.

FJSRL-TM-82-0018, "Programmable Input/Output and Time of Day Clockboard," by Maj J. Pollard and A1C P. Earl, Sep 82.

FJSRL-TM-83-0002, "Closed Loop Control for Large PRRLG Stabilization," by Lt Gary Richter, Maj Joseph Pollard, and Mr. Bill Simmons, Jan 83.

FJSRL-TM-83-0009, "FJSRL Z-80A HPIB Interface Board," by Maj Joseph Pollard and A1C Pamela Earl, May 1983.

FJSRL-TM-83-0010, "FJSRL Z-80A 16K RAM Overlay Board," by Maj Joseph Pollard and A1C Pamela Earl, May 1983.

FJSRL-TM-83-0011, "A Data Acquisition System for the Passive Resonant Ring Laser Gyroscope," by Major Joseph Pollard and MSgt Earl Barr, May 1983.

FJSRL-TM-83-0012, "A Non-Linear Controller for Laser Stabilization Applications," by Major J.J. Pollard, Major S.R. Balsamo, and A1C P.K. Earl, May 1983.

FJSRL-TM-83-0011, "A Data Acquisition System for the Passive Resonant Ring Laser Gyroscope," by Maj J.J. Pollard and MSgt E.L. Barr, May 83.

FJSRL-TM-84-0005, "Robust Upgrade of Low Frequency Servo in Support of Passive Resonant Ring Laser Gyroscope," E6 Andrew P. Hardy, Dec 84.

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