NASA TECHNICAL MEMORANDUM

NASA TM X-64915

(NASA-TM-X-64915) LAGEOS PHASE B TECCHNICAL REPORT (NASA) 109 p HC $5.25 CSCL 22B

N75-19323

Unclas

G3/15 13431

LAGEOS PHASE B TECHNICAL REPORT

February 1975

NASA

George C. Marshall Space Flight Center
Marshall Space Flight Center, Alabama

TECHNICAL REPORT STANDARD TITLE PAGE

1. REPORT NO. TMX-64915	2. GOVERNMENT ACCESSION NO.	3. RECIPIENT'S CATALOG NO.
4. TITLE AND SUBTITLE LAGEOS Phase B Technical Report		5. REPORT DATE February 1975
		6. PERFORMING ORGANIZATION CODE EE01
7. AUTHOR(S) Science and Engineering Directorate		8. PERFORMING ORGANIZATION REPORT #
9. PERFORMING ORGANIZATION NAME AND ADDRESS Associate Director for Engineering Science and Engineering Marshall Space Flight Center, Alabama 35812		10. WORK UNIT NO.
		11. CONTRACT OR GRANT NO.
		13. TYPE OF REPORT & PERIOD COVERED Technical Memorandum
12. SPONSORING AGENCY NAME AND ADDRESS		14. SPONSORING AGENCY CODE
15. SUPPLEMENTARY NOTES		

16. ABSTRACT

The LASER Aerodynamic Satellite (LAGEOS) Phase B study is a follow-on to work performed on the Smithsonian Earth Physics Satellite. The efforts of this study are to perform analysis and design of the Satellite and to integrate the design with the launch vehicle interfaces and launch operations. The Satellite has a basic requirement to be compatible with techniques for ranging from earth to Satellite to an accuracy of ± 2 cm. Range measurements to this level of accuracy are necessary to accomplish many of the objectives of the Earth and Ocean Physics Application Program (EOPAP).

The results of the study indicate the Satellite design while maintaining low program cost, met the overall Level I design and mission requirements. Trade studies and Satellite design along with thermal and optical tests performed by Bendi : Corporation are documented in this report.

17. KEY WORDS	18. DISTRIBUTION STATEMENT Unclassified - Unlimited Lewis L. McNair Lewis L. McNair LAGEOS Chief Engineer

19. SECURITY CLASSIF. (of this report) Unclassified	20. SECURITY CLASSIF. (of this page)	21. NO. OF PAGES	22. PRICE

MSFC - Form 3292 (Rev December 1972)

For sale by National Technical Information Service, Springfield, Virginia 22151

ACKNOWLEDGMENTS

The Office of Applications, NASA Headquarters, provided the funds, overall Program Guidelines and Level I Requirements, which included the Mission and Scientific Requirements for the Phase B activities.

The MSFC served as the lead NASA Center with the LAGEOS Task Team under Program Development providing the overall program management aspects of the MSFC and contractor activities.

The engineering analysis, Satellite design, and launch vehicle integration were performed by the Science and Engineering Directorate. The LAGEOS Chief Engineer was responsible for the overall management and integration of the Science and Engineering activities. The organizations within Science and Engineering that participated in the activities are:

Electronics and Control Laboratory
Structures and Propulsion Laboratory
Systems Analysis and Integration Laboratory
Systems Dynamics Laboratory
Test Laboratory
Materials and Processes Laboratory
Reliability and Quality Assurance Office

The Bendix Corporation and the ITEK Corporation assisted in the Phase B study with a contract to perform analysis and test in the thermal, optics and vibration areas.

The Goddard Space Flight Center in conjunction with MDAC provided the launch vehicle definition, the attach mechanisms and the separation systems.

TABLE OF CONTENTS

List of Figures

List of Tables

LIST OF ABBREVIATIONS

ALSEP	Apollo Lunar Surface Experiments Package
CCBD	Configuration Control Board Directive
CG	Center of Gravity
cm	Centimeter
CCR	Cube Corner Retroreflector
EOPAP	Earth and Ocean Physics Application Program
FFDI	Far Field Diffraction Instrument
FFDP	Far Field Diffraction Pattern
GEOS	Geodynamic Experimental Ocean Satellite
ICD	Interface Control Document
LAGEOS	Laser Geodynamic Satellite
mm	Millimeter
MSFC	Marshall Space Flight Center
NASA	National Aeronautics and Space Administration
OA	Office of Applications, NASA Headquarters
OPD	Optical Path Differences
TBD	To Be Determined
UT	Universal Time
WTR	Western Test Range

1.0 Introduction and Background

1.1 Introduction

In response to a request from the Office of Applications, NASA Headquarters, the George C. Marshall Space Flight Center performed a detail Phase B analysis and design of the LASER Geodynamic Satellite (LAGEOS). This was a follow-on design activity to work that had been performed by MSFC on the Smithsonian Earth Physics Satellite in 1971 (Reference 1). A Task Team was organized under Program Development with the engineering analysis and design being performed by Science and Engineering. Bendix Corporation and ITEK assisted in the overall study with a contract to perform analysis and test in the thermal, optics, and vibration areas. Scientific requirements are a responsibility of OA, NASA Headquarters and the Launch Vehicle (Thor/Delta) is the responsibility of Goddard Space Flight Center.

This report documents the Phase B technical aspects and design of the Satellite, Launch Vehicle Interfaces, and Launch preparation. The programmatic aspects are documented under separate cover.

1.2 Approach and Study Objectives

The basic approach for the analysis and design of the Satellite utilized MSFC in-house manpower supplemented by analysis and test work under Contract Number NAS8-30658 to Bendix Corporation. The Delta Launch Vehicle System (LVS) is furnished and managed by Goddard Space Flight Center. The more specific details of MSFC and GSFC responsibilities for the LAGEOS Project are given in the Memo of Agreement dated August 17, 1974. Figure 1-1 depicts the overall LAGEOS Project management relationships and Figure 1-2 shows the MSFC Phase B Study Team.

The Phase B overall study objective for the Satellite was to analyze, design, and test at the lowest program cost compatible with the scientific performance and design specifications. Additionally, the Launch Vehicle Interfaces, Satellite Shroud, Satellite Supporting Structure, and the Satellite Ejection System were to be sufficiently defined and designed on a low cost basis to meet the overall mission requirements. These objectives were met in the Phase B study.

FIGURE 1-1

PHASE B

LAGEOS MANAGEMENT RELATIONSHIP

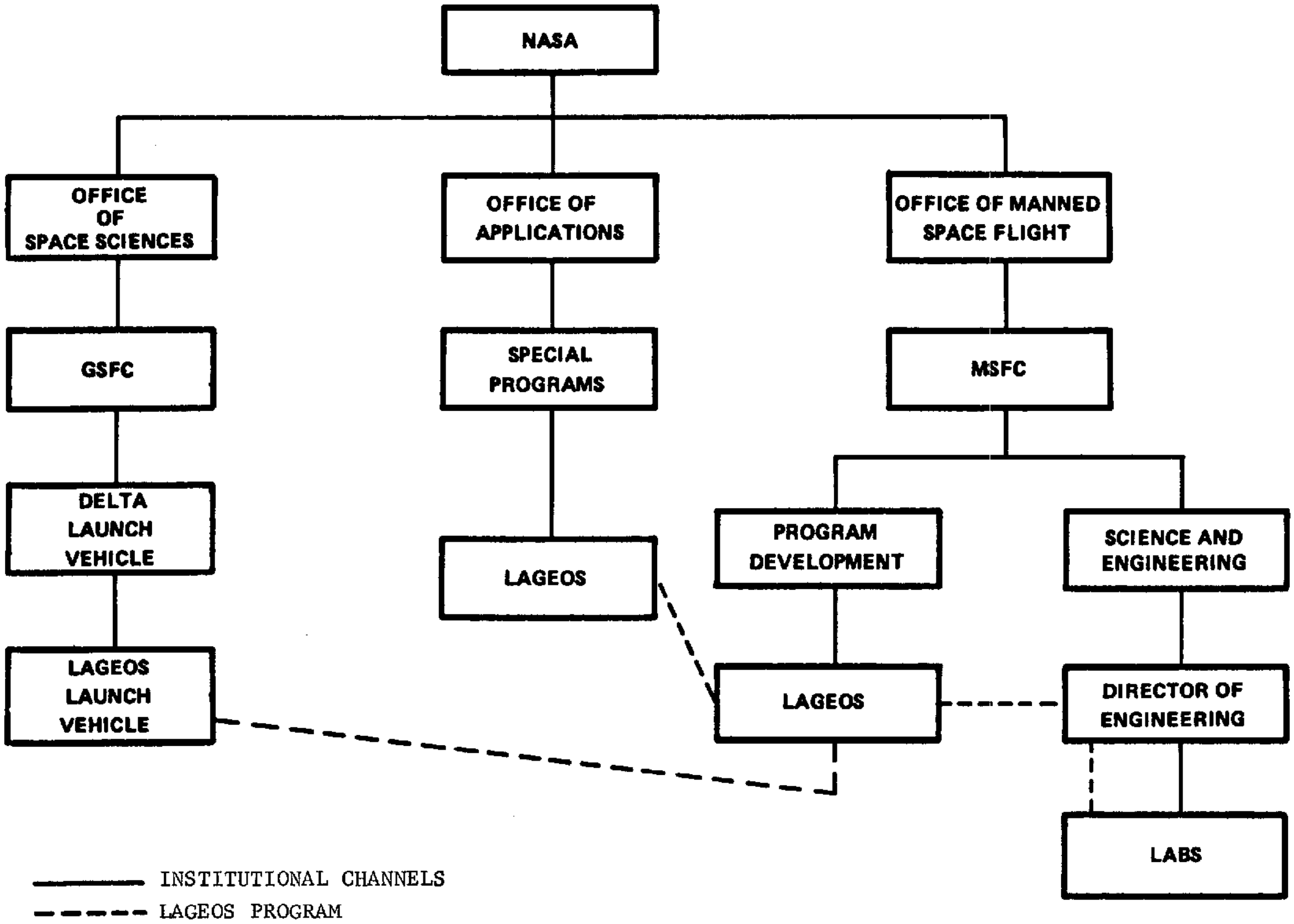


Figure 1-2

MSFC Phase B Study Team

Program Development

Don Bowden - LAGEOS Task Team Manager

Bill Johnson - LAGEOS Engineering Manager

Byron Crider - Program Control

Science and Engineering

Lewis L. McNair - LAGEOS Chief Engineer

Ron Creel - Thermal

Joe Randall/Jim Zurasky - Optics

Ozzie Harrison/Jake Lysaght - Structures & Design

Harold Johnson - Specification & Configuration Management

Jim McBride/John Admire - Vibration & Dynamics

Neil Allen/Bill Eoff - Dynamic Test

Jim Moseley/Merle Jones - Manufacturing

Anne Folsom - Quality & Reliability

John Moore - Retroreflector Pattern Analysis

1.3 Science Background

One of the principal recommendations of the Williamstown Study on solid-earth and ocean physics (Kaula, 1969) was that NASA develop techniques for ranging to satellites to an accuracy of ± 2 cm. Range measurements at this level of accuracy will be necessary to accomplish many objectives of the Earth Physics Program (EPP), such as the determination of plate tectonic motions (continental drift), rotation variations and wobble of the earth, earth body tides, etc. These objectives must be attained by measuring the temporal variations of the following: the geometry of a global matrix of fiducial points on the earth's surface; the fiducial points with respect to the earth's center of mass; and the matrix with respect to an inertial reference. These geometric variations are known to have time scales ranging from a day (e.g., body tides) to millenia (continental drift).

What is needed is a means for making exceedingly accurate measurements on a global basis in such a way that, first, each position on the globe can be related to all others; second, complete sets of observations can be obtained in less than a day; and third, continuity of observations is maintained over the longest possible time span. The first two considerations clearly suggest the use of a satellite in a high-inclination orbit; the third suggests that the satellite be passive. It is concluded that a high-density satellite fitted with laser retroreflectors is an appropriate choice.

This Satellite will make available, for the foreseeable future, an in-orbit capability for laser ranging of maximum accuracy. The high mass/area ratio and the precise, stable (attitude independent) geometry of the spacecraft in concert with the proposed orbit will make this Satellite the most precise position reference available. Because it will be visible to all parts of the world and will have an extended operating life in orbit, the Satellite can serve as a fundamental global standard for decades. It would constitute an important first step in the NASA Earth Physics Program.

1.3.1 Scientific Objectives

This Satellite was conceived for a single purpose: to measure positions on earth to an accuracy of at least 10 cm (goal of ± 2 cm). This is basic to NASA's Earth Physics Program since many of the program's objectives will not be met without this capability. Some of these objectives are to measure or establish the following:

a. Rotation of the earth

b. Polar motion

c. Earth body tides and tidal loading

d. Tectonic motions

e. A 10-cm terrestrial coordinate system

1.3.1.1 Rotation of the Earth

The rate of rotation of the earth is equivalent to UT-1*. The EPP objectives are to measure rotation to a relative accuracy of 0.002 arc second (130μ sec, UT-1) for averaging times less than one day, to an absolute accuracy of 0.01 arc second (650μ sec, UT-1) for averaging times of one day, and to an absolute accuracy of 0.01 arc second relative to an inertial coordinate system over decades. The periods of some components of rotational variations are known, namely, tidal and seasonal. The remaining components have been classified as irregular with a spectrum that encompasses the entire frequency range now observable with available instruments.

1.3.1.2 Polar Motion

The accuracy requirements for the measurement of polar motion are the same as those for measuring the rotation rate. Two aspects of polar motion must be distinguished: motion of the spin axis with respect to inertial coordinates, and motion of the earth with respect to its spin axis. The periods of several components of polar motion have been identified or suggested, namely, diurnal, tidal, seasonal, 1.2-year, 18.6-year, 24-year, and secular.

1.3.1.3 Earth Body Tides and Tidal Loading

These effects are vertical motions of the earth's surface, with maximum amplitude of the order of 50 cm and with a spectrum of discrete and very accurately known frequencies. The pertinent observational data should provide an accuracy of at least ± 10 cm (in the vertical) for averaging times of several hours or less.

1.3.1.4 Tectonic Motions

Tectonic motions are of very great scientific interest but are extremely difficult to measure. It is desirable to attain an accuracy of at least 10 cm (1 cm would be much better) both horizontally and vertically in determining the relative positions of the

* Universal Time corrected for the earth's polar variations.

Major tectonic plates. It would also be of considerable interest to determine the stability or rigidity within each plate.

1.3.1.5 Establishment of a 10-cm Terrestrial Coordinate System

In the words of the Williamstown Study, "The terrestrial system will be defined by coordinates assigned to a number of stations and their time variations. This system should have as its origin the earth's center of mass and as a Z-axis the principal axis of inertia, as determined from satellite dynamics considerations". Thus, the satellite must be designed to be used for observations in such a way that its orbit can be determined to an accuracy consistent with the accuracy needed to define the coordinate system.

1.4 Satellite Requirements and Configuration

1.4.1 Requirements

A satellite that is optimum for EOPAP geometric measurements would be characterized in the following way:

a. Completely passive to attain maximum operating life. Acquired by camera (photographing reflected sunlight against star background). Equipped with retroreflectors for ranging with ground-based lasers.

b. Compact and rigid for stability of spacecraft geometry.

c. Spherical geometry of retroreflector array versus spacecraft center of mass will not change with aspect. Spherical shape also necessary to minimize errors in computing corrections for radiation pressure and drag.

d. Maximum feasible mass-to-area ratio to reduce perturbations caused by nongravitational forces (mainly radiation pressure).

e. Orbital altitude high enough to reduce to an acceptable level orbit errors resulting from uncertainties in geopotential models.

f. Orbital altitude low enough to provide strong geometry, good signal-to noise ratios with a retroreflector array of reasonable dimensions.

g. Inclination large enough to provide global coverage.

1.4.2 Study Assumptions

The study assumptions or guidelines were derived from the more general requirements that appear in paragraph 2.1 and in the Level I Specification ES-LA-100. Some of the more salient requirements are listed below with a more complete listing found in Specification ES-LA-100 (Reference 2).

<u>Mission Requirements</u>

	Nominal Value	Approximate Range
Altitude	5900 Km	TBD*
Inclination	110°	TBD*
Eccentricity	0	.013

* Includes the potential variations due to launch vehicle injection deviations.

<u>Satellite Structure</u>

Structural configuration - Spherical

	Nominal Value	Approximate Range
Diameter	60 cm	50 - 60 cm
Weight	385 Kg	300 - 600 Kg
Ratio of Moment of Inertia	≥ 1.03	

The center of mass should coincide with the center of geometry to within ± 1 mm. The variation of the retroreflector apex from the nominal installation position shall not exceed ± 1.0 mm in the radial direction and ± 2.0 mm in the direction normal to the radial direction.

The satellite thermal and optical characteristics are indicated in chapters three and four.

2.0 Design Considerations and Selection

2.1 Satellite Configuration

The LAGEOS satellite is a passive sphere 60 centimeters in diameter weighing 906 pounds. The outer surface is equipped with 426 cube corner retroreflectors to reflect ground based laser beams. The moment of inertia about the X (flight direction) axis divided by that about the Y (or Z) axis is required to be greater than 1.03 to ensure spin about the X axis after spin-up and insertion into orbit.

2.2 Configurations Investigated

In the Phase B study, four configurations, or rather assembly schemes, were evaluated. First, a solid sphere was studied which has the advantage of simplicity since there is only one part, and therefore, no assembly problems. This advantage in fabrication simplicity; however, is more than offset by the disadvantage of not being able to alter the weight or moment of inertia within a given sphere size. The second configuration investigated consisted of a cylindrical counterweight embedded in two aluminum hemispheres as shown in Figure 2-1. This configuration is somewhat more complicated to machine and any arrangement of the retroreflectors would have to avoid the assembly joint at the equator. It was possible; however, to alter weight and moment of inertia in this configuration by altering diameter, length, and material of the counterweight. Another variation of the above scheme comprised the third configuration and is shown in Figure 2-2. Two spherical segments and a zone were combined with a central counterweight to provide the desired weight and moment of inertia. This was a slightly more complicated configuration and had the disadvantage of two parting lines to be avoided by the retroreflector pattern.

ORGANIZATION:	MARSHALL SPACE FLIGHT CENTER	NAME:
STRUCTURES AND PROPULSION LAB	LAGEOS DESIGN CONCEPT B	J. O. LYSAGHT
		DATE: SEPT. 1974

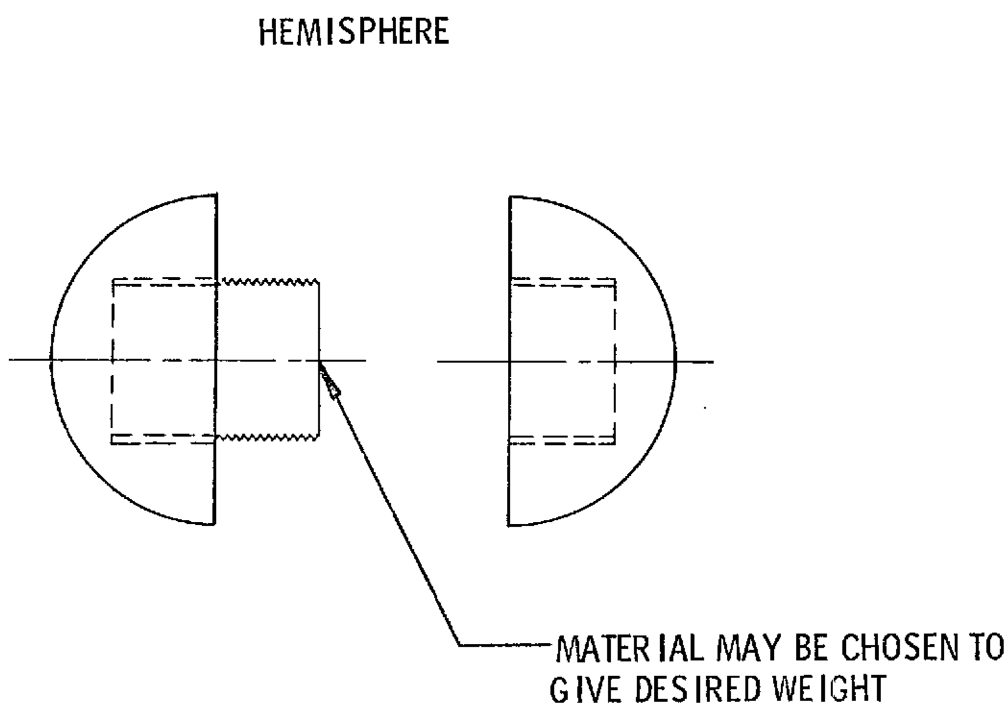


Figure 2-1 LAGEOS Design Concept B

ORGANIZATION:	MARSHALL SPACE FLIGHT CENTER	NAME:
STRUCTURES AND PROPULSION LAB	LAGEOS DESIGN CONCEPT C	J. O. LYSAGHT
		DATE: SEPT. 1974

SPHERICAL SEGMENTS
& ZONE

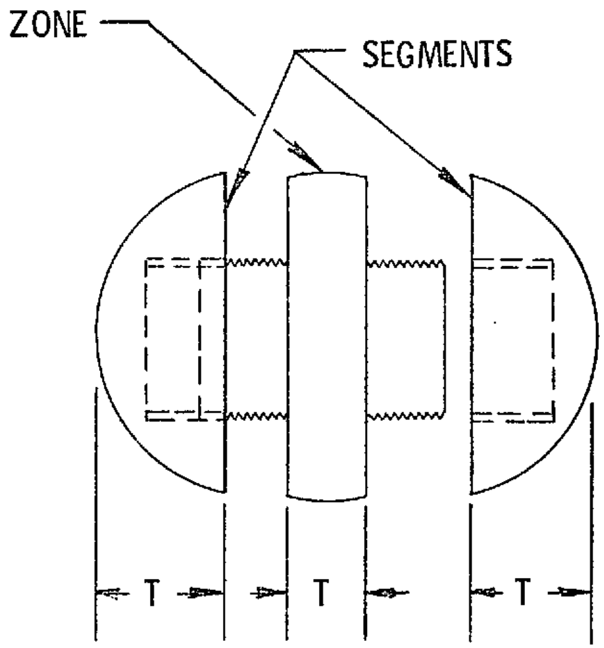


Figure 2-2 LAGEOS Design Concept C

The most versatile, in terms of weight and moment of inertia tailoring, was provided by the fourth scheme and is shown in Figure 2-3. This configuration was, by far, the most intricate and costly to fabricate and has the further disadvantage of six joint lines about which the retroreflectors must be assembled, resulting in fewer retroreflectors being mounted in a given diameter.

2.3 Selected Configuration

The configuration selected for fabrication was a variation of the second one discussed above and is shown in Figure 2-4. The two 6061 aluminum hemispheres with a spherical radius of 30 centimeters are counterbored to accept a brass bolt. The nuts and washers on the through-bolt are embedded in cavities under the retroreflectors located at the north and south poles of the sphere. Four hardened (200,000 psi tensile equivalent) inserts are equally spaced around the equator of the sphere on the parting line of the two hemispheres. These inserts mate with four spherical fittings on the separation mechanism of the Delta Launch Vehicle. Details of the assembly are depicted on MSFC Drawing 30M20460.

A computer program was developed to determine optimum number and maximum symmetry of corner cube retroreflectors, mounted in 4.76 cm diameter holes, in each hemisphere. A total of 213 retroreflectors per hemisphere are located as shown in Figure 2-5 and on MSFC Drawing 30M20459. A cross section through a retroreflector, mounted in its cavity is shown in Figure 2-6.

To ensure maximum return of energy from the ground based laser, the retroreflectors are arranged in a pattern such that a real edge of any retroreflector makes an angle of 94° degrees with a real edge of any of its neighbors. The

ORGANIZATION: STRUCTURES & PROPULSION	MARSHALL SPACE FLIGHT CENTER LAGEOS DESIGN CONCEPT D	NAME: J. O. LYSAGHT DATE: FEBRUARY 1975

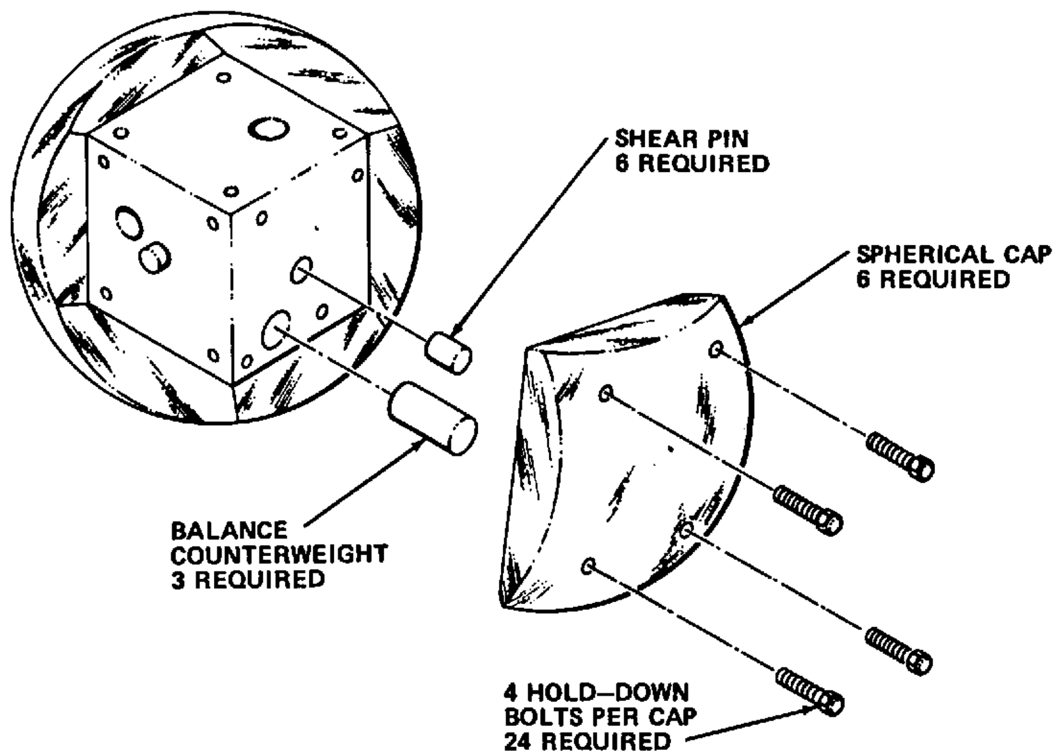


FIGURE 2–3 LAGEOS DESIGN CONCEPT D

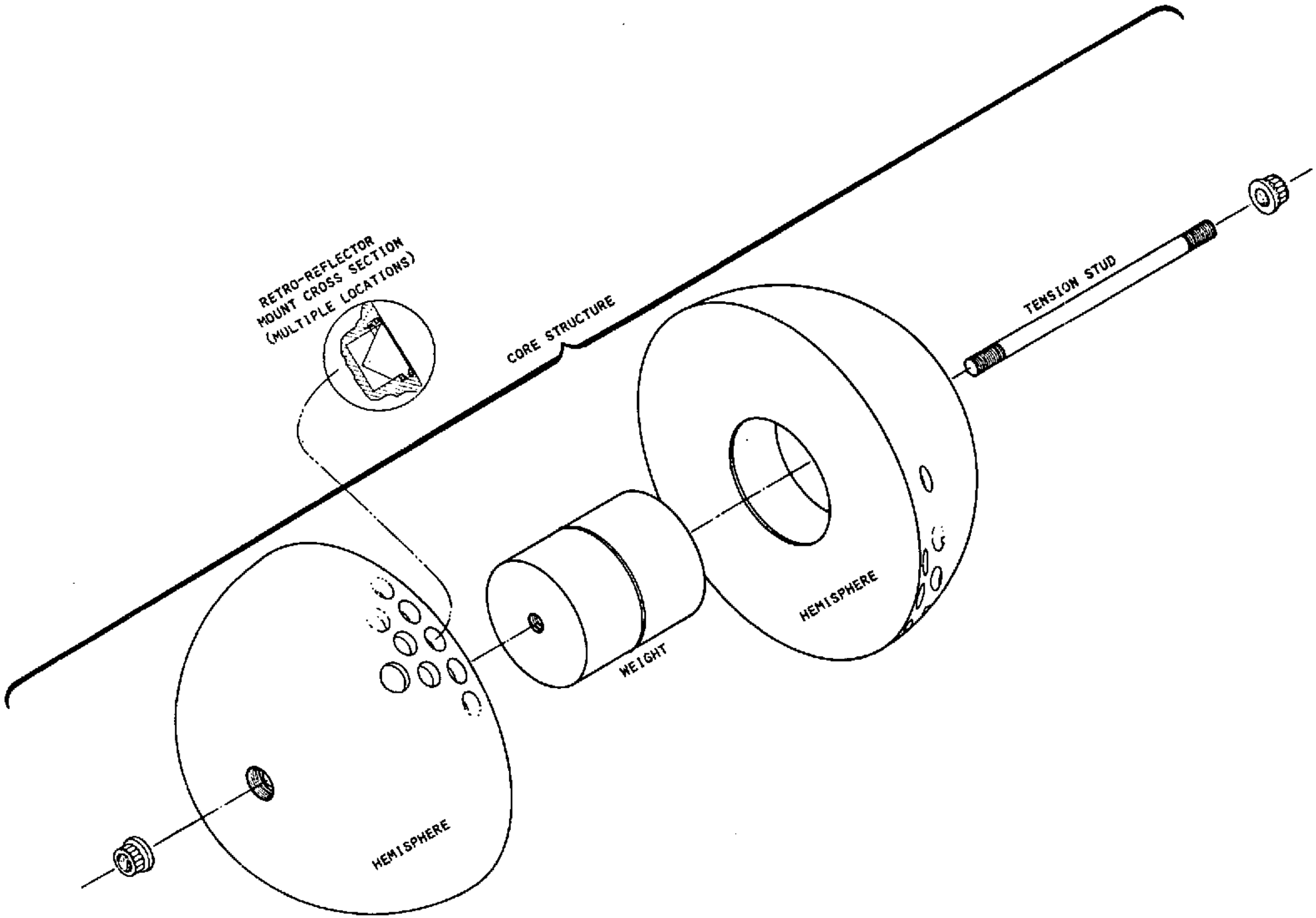
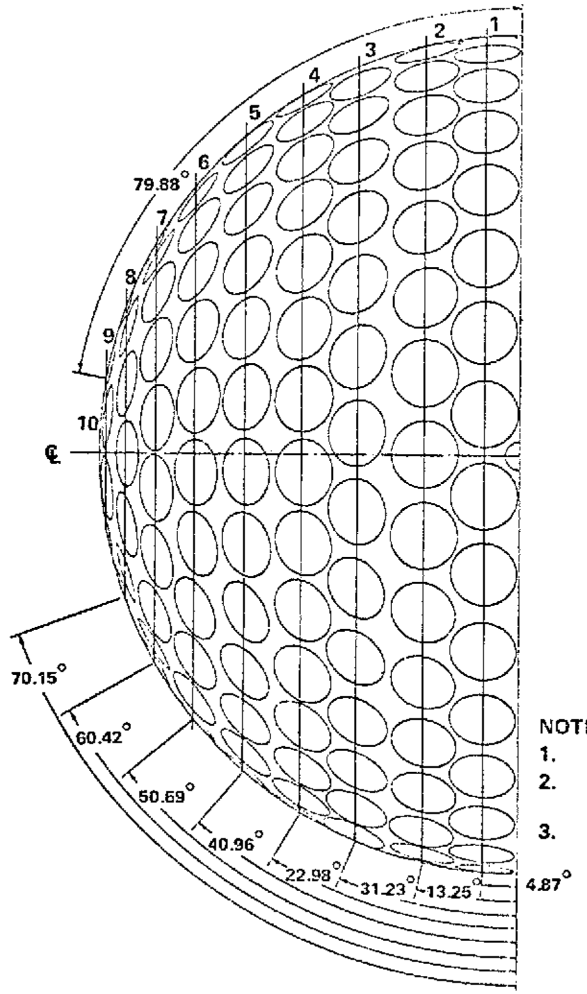


Figure 2-4 LAGEOS Satellite Configuration

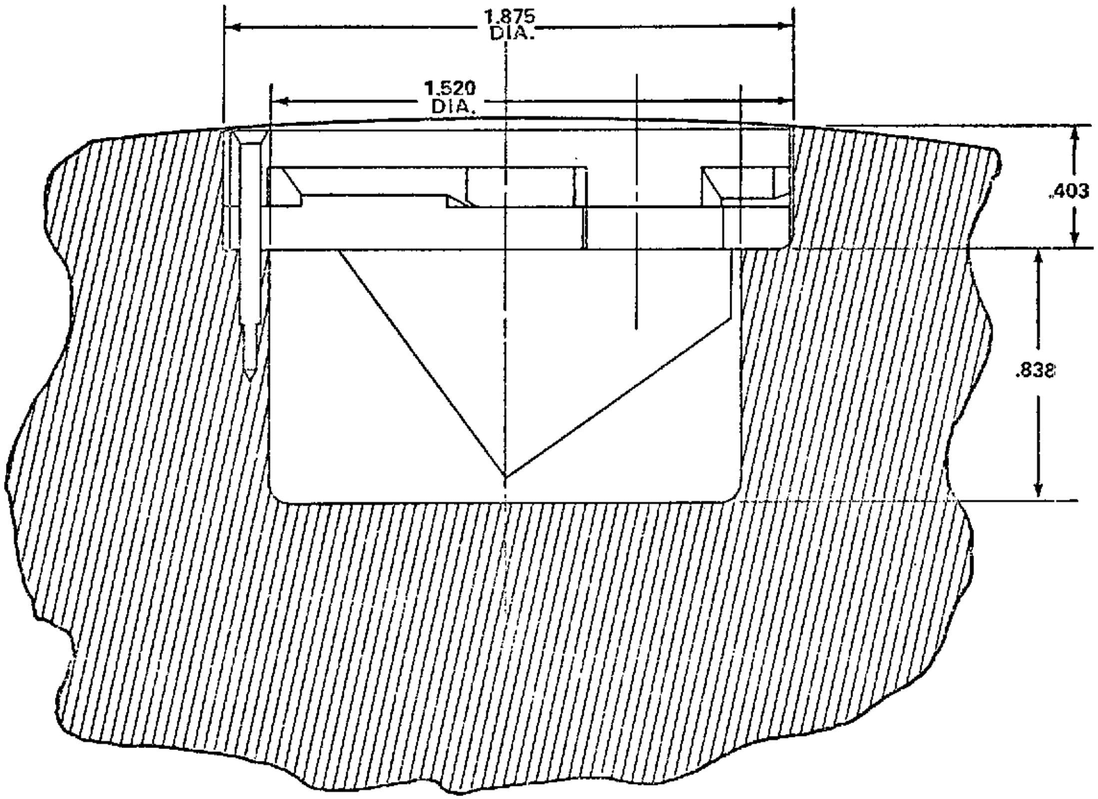
ORGANIZATION:	MARSHALL SPACE FLIGHT CENTER	NAME: J. O. LYSAGHT
STRUCTURES & PROPULSION	LAGEOS HALF SPHERE CONCEPT 23.633 DIA., 1.875 DIA. HOLES	DATE: SEPT 1974



NOTES:
1. RINGS 1 & 2 AND 3 & 4 ARE MESHED.
2. HOLES ARE EQUALLY SPACED IN CONCENTRIC RINGS. SEE TABLE.
3. ALL HOLES ARE LOCATED FROM +Z AXIS.

Figure 2-5 LAGEOS Half Sphere Concept

ORGANIZATION: STRUCTURES & PROPULSION	MARSHALL SPACE FLIGHT CENTER RETROREFLECTOR INSTALLATION	NAME: J. O. LYSAGHT DATE: SEPT 1974



TYP 426 PLACES

Figure 2-6 Retroreflector Installation

table of information required to drill the 1278 holes for the retroreflector retaining screws is on MSFC Drawing Number 30M20459.

2.4 Geometrical Placement of Cube Corner Retroreflectors

A systematic procedure was devised for placing the "maximum" number of cube corner retroreflectors (CCR's) on the spherical satellite while achieving a reasonable amount of the desired symmetry. This section describes the procedure and presents some of the trade data used in selecting the size and relative spacing of the CCR attachment holes.

The satellite is to be constructed from two hemispheres. CCR's are symmetrically placed in rings about each hemisphere. The desired minimum distance between CCR's in adjoining rings is achieved by control over the width of the rings. Note that absolute symmetry is achieved about the polar axis and between the two hemispheres. Only approximate symmetry is obtained about an axis in the equatorial plane. Total symmetry cannot be obtained by any procedure because no CCR's may be placed in the joint between the two hemispheres. Here, the joint is assumed to be in the equatorial plane of the sphere.

The procedure provides a simple and accurate way of identifying the location of each CCR (via latitude and longitude). The task of drilling the holes in which the CCR's are placed could be easily automated.

The ring placement procedure can be modified to increase the number of CCR's placed on a fixed diameter sphere. The modification involves "meshing" rings which contain approximately the same number of CCR's. This concept can best be explained by an example. Suppose 40 CCR's can be placed in the first ring above the hemisphere joint and 39 CCR's can be placed in the second ring above the joint. The modified procedure would place 39 CCR's in both rings. This allows the second ring to be placed closer to or meshed with the first ring. The two meshed rings will require less surface area than two unmeshed rings. The meshing technique is applied to the third and fourth rings, the fifth and sixth rings, etc., until the point of diminishing returns is reached. For example, meshing a ring that can contain nine CCR's with a ring that can contain only five CCR's is obviously not advantageous. Meshing is stopped once the difference between the number of CCR's in two adjoining rows becomes more than a predetermined constant. For a sixty centimeter diameter sphere and a 4.76 centimeter diameter CCR hole, a value of 2 or 3 is reasonable for this constant.

The meshed and unmeshed (single ring) procedures were implemented in a computer code. Given the sphere diameter, the hole diameter in

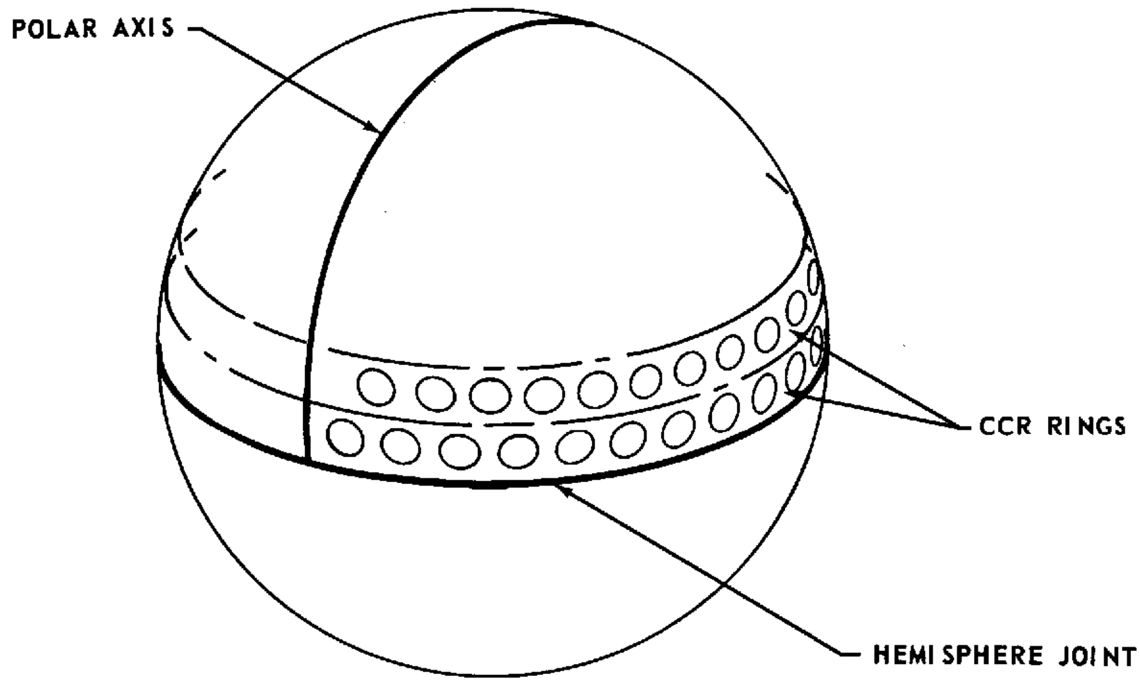


FIGURE 2-7 GEOMETRICAL PLACEMENT OF CCR'S

which CCR's are placed, the hole depth, and the minimum allowable distance between the bottoms of two adjacent holes, the code specifies the number of rings, the number of CCR's in each ring, the latitude of each ring, and the total number of CCR's placed.

The computer code was used to parameterize the number of CCR's that may be placed on the satellite as a function of (1) sphere diameter, (2) CCR hole diameter, (3) hole depth, and (4) the minimum distance between the bottoms of adjacent holes. Two other variables that are dependent upon the above four variables were also computed. One is the percent of spherical surface area that is removed by the CCR holes. (In order for a ground tracking camera to see the satellite in orbit, at least 35 percent of the spherical surface area must remain to reflect light.) The other parameter is the range of surface distances between adjacent CCR holes. This range provides some measure of symmetry. A wide range indicates poor symmetry. Similarly, a narrow range indicates good symmetry.

Table 2-1 presents trade data for the unmeshed or single ring placement concepts. Table 2-2 presents trade data for the meshed placement concept. The meshed concept places approximately 3 percent more CCR's than the single ring concept. But the single ring concept has a more consistent placement pattern. The meshed concept provides a close pattern among CCR's within two meshed rings, however, the pattern between pairs of meshed rings is identical to the pattern between individual rings in the single ring concept. Trade data for other satellite diameters are presented in the reference.

Drawing number 30M20459 baselined by CCBD LA-74-0004 and LA-74-0005 provides a description of the satellite geometry selected during the Phase B study. This configuration places 426 CCR's on the satellite. The CCR's are placed in holes which are 4.76 cm in diameter. The minimum distance between the bottom of any two holes is 0.15 cm.

2.5 CCR Mounting Configuration

The design and development of the LAGEOS Satellite CCR Mount began with the evaluation and testing of the CCR's and their mounts as used in the GEOS and ALSEP programs. The hardware and test reports from these two programs offered two divergent configuration approaches to be considered in the LAGEOS design, in that; the ALSEP concept thermally isolates the CCR from the Satellite body and the GEOS allows the CCR to seek the body temperature through a metallic mounting clip. The configurations were studied and the thermal analysis indicated that the isolated mount would allow the CCR's to perform better and would be easier to model for various operational conditions; therefore, an isolated mount was selected as best satisfying the LAGEOS requirements.

TABLE 2 - 1

SINGLE RING PLACEMENT CONCEPT
(60 cm DIAMETER SPHERE)

HOLE DEPTH (CM)	HOLE DIAMETER (CM)	MIN. DISTANCE BETWEEN BOTTOM OF HOLES (CM)	NUMBER OF CCR's	VARIATION BETWEEN HOLES ON SURFACE OF SPHERE (CM)	SURFACE COVERED BY HOLES FOR CCR's (%)	
2.70	4.76 [a]	.000	398	.60 to 1.10	49.4	
2.70		.025	394	.60 to 1.13	48.9	
2.70		.051	390	.60 to 1.15	48.4	
2.70		.076	386	.60 to 1.18	47.9	
2.10		.000	420	.45 to .97	52.2	
2.10		.025	418	.45 to .99	51.9	(c)
2.10		.051	412	.45 to 1.02	51.2	
2.10		.076	404	.45 to 1.04	50.2	
1.60		.000	440	.31 to .86	54.6	
1.60		.025	430	.31 to .88	53.4	
1.60		.051	422	.45 to .94	52.4	
1.60		.076	422	.45 to .96	52.4	
1.29		.000	442	.31 to .81	54.9	
1.29		.025	440	.31 to .83	54.6	
1.29		.051	440	.31 to .86	54.6	
1.29		.076	430	.31 to .88	53.4	
3.16	4.45 [b]	.000	449	.63 to 1.12	61.0	
3.16		.025	440	.63 to 1.15	60.5	
3.16		.051	440	.63 to 1.17	60.5	
3.16		.076	430	.63 to 1.20	59.1	

(a) TEFLON RETAINING RINGS ARE USED TO HOLD CCR's IN 4.76 CM DIAMETER HOLES.

(b) THREE PRONG CLIPS ARE USED TO HOLD CCR's IN 4.45 CM DIAMETER HOLES.

(c) AREA OF TEFLON RETAINING RING SUBTRACTED FROM HOLE AREA BEFORE PERCENT OF SURFACE COVERED WAS COMPUTED.

TABLE 2 - 2

MESHED RING PLACEMENT CONCEPT
(60 cm DIAMETER SPHERE)

HOLE DEPTH (CM)	HOLE DIAMETER (CM)	MIN. DISTANCE BETWEEN BOTTOM OF HOLES (CM)	NUMBER OF CCR's	VARIATION BETWEEN HOLES ON SURFACE OF SPHERE (CM)	SURFACE COVERED BY HOLES FOR CCR's (%) [c]
2.70	4.76 [a]	.000	412	.47 to .99	51.2
2.70		.025	410	.54 to 1.06	50.9
2.70		.051	406	.53 to 1.18	50.4
2.70		.076	400	.56 to 1.17	49.7
2.10		.000	432	.42 to .91	53.6
2.10		.025	428	.41 to .93	53.2
2.10		.051	424	.41 to 1.00	52.7
2.10		.076	420	.47 to 1.03	52.2
1.60		.000	448	.28 to .80	55.6
1.60		.025	442	.33 to .87	54.9
1.60		.051	442	.32 to 1.16	54.9
1.60		.076	434	.47 to .95	53.9
1.29		.000	456	.21 to 1.00	56.6
1.29		.025	454	.33 to 1.09	56.4
1.29		.051	448	.29 to .80	55.6
1.29		.076	442	.33 to .87	54.9
3.16	4.45 [b]	.000	456	.53 to 1.03	62.7
3.16		.025	454	.65 to 1.14	62.4
3.16		.051	450	.61 to 1.12	61.8
3.16		.076	442	.61 to 1.15	60.7

(a) TEFLON RETAINING RINGS ARE USED TO HOLD CCR's IN 4.76 CM DIAMETER HOLES.

(b) THREE PRONG CLIPS ARE USED TO HOLD CCR's IN 4.45 CM DIAMETER HOLES.

(c) AREA OF TEFLON RETAINING RING SUBTRACTED FROM HOLE AREA BEFORE PERCENT OF SURFACE COVERED WAS COMPUTED.

ORGANIZATION:	MARSHALL SPACE FLIGHT CENTER	NAME: J. L. ZURASKY
ASTRIONICS	CCR - CONFIGURATION AND INSTALLATION CONCEPTS	DATE: 12/20/73

CUBE CORNER
MOUNTING COMPARISON

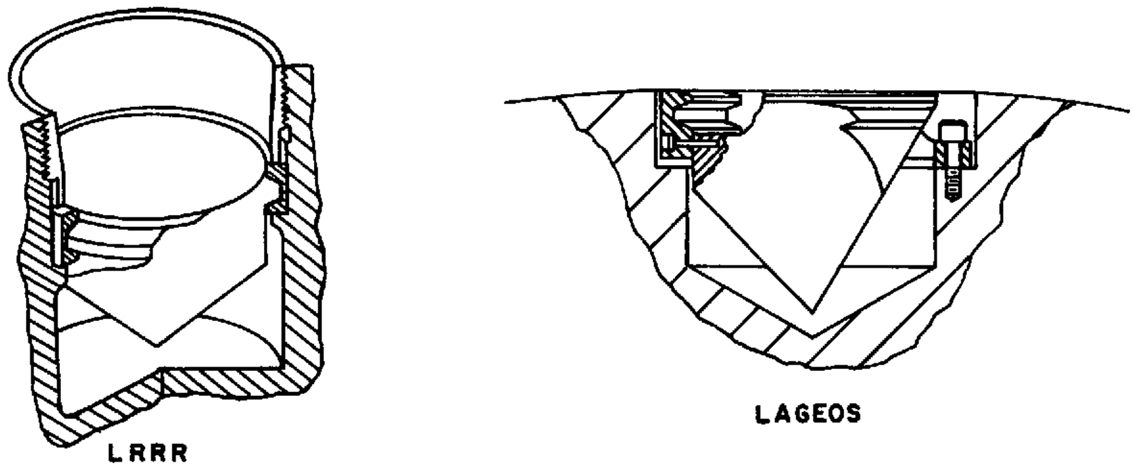


FIGURE 2-8 CCR CONFIGURATION AND INSTALLATION CONCEPTS

ORGANIZATION:	MARSHALL SPACE FLIGHT CENTER	NAME: RALPH GRUBB
ELECTRONICS & CONTROL	GEOS CCR MOUNTING	DATE: SEPT. 4, 1974

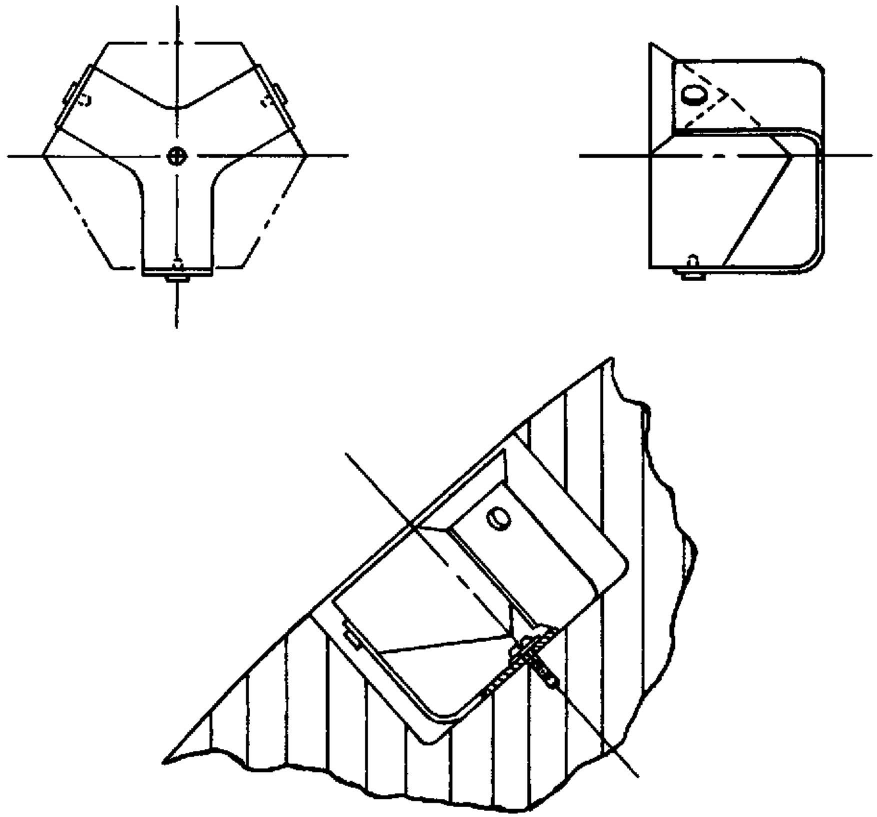


FIGURE 2-9 GEOS CCR MOUNTING

ORGANIZATION:	MARSHALL SPACE FLIGHT CENTER	NAME:
ELECTRONICS & CONTROL	LAGEOS CCR - CONFIGURATION AND INSTALLATION CONCEPTS	RALPH GRUBB
		DATE: SEPT. 4, 1974

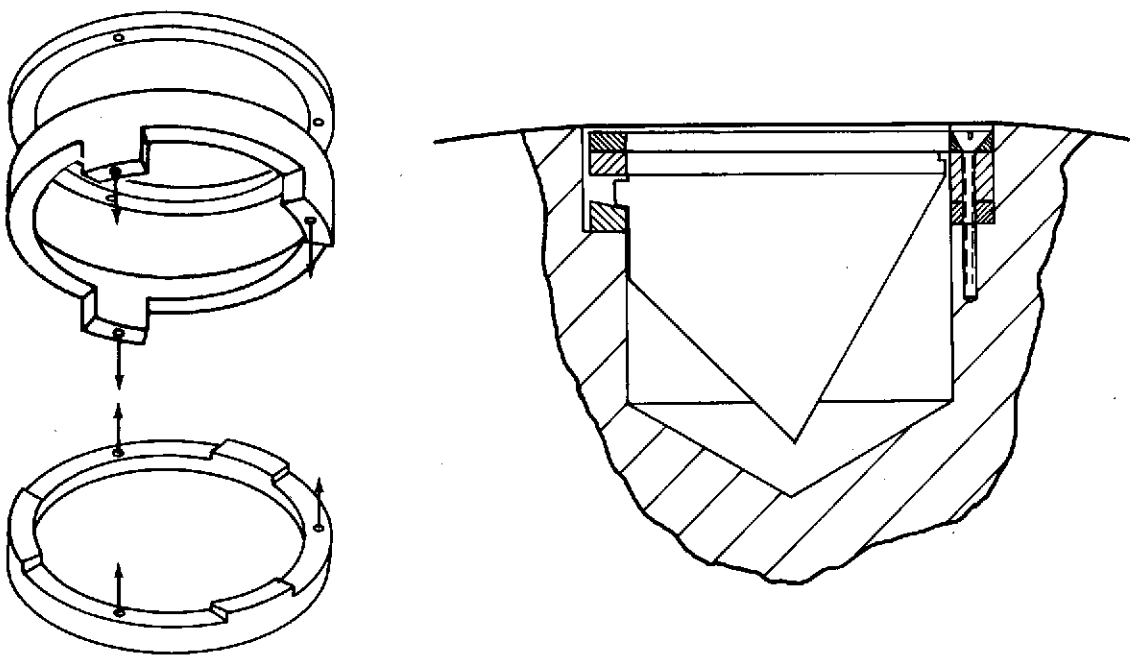


FIGURE 2-10 LAGEOS CCR–CONFIGURATION AND INSTALLATION CONCEPTS

Other design parameters used to develop the LAGEOS CCR Mount are as follows:

a. A cost effective approach was followed in all aspects of the design and work requirements. Simple fabrication methods and techniques were used and allowances were made for corrective rework when and if it was required.

b. The material selected for the CCR Mount must satisfy the thermal isolation and outgassing requirements and, it must be a stable material that is easy to machine. "Kel-F", a plastic resin material, was selected because it meets all these requirements. It is thermally stable from -400 to +400 deg. F; abrasion resistant; resistant to a wide range of chemicals and fuels; an excellent thermal isolator and has zero moisture absorption qualities.

c. The design must satisfy the thermal and accuracy requirements. The thermal characteristics of the Kel-F material with the machine tolerances imposed on the mount design meet all the thermal and accuracy requirements while providing a practical method to measure and confirm the requirements.

In summary, the CCR's and their mounts provide the LAGEOS Satellite Program with a simple, straight forward mounting concept that meets the accuracy requirements, provides for a mounting concept with a CCR free from external stresses and thermally isolated from the Satellite body.

2.6 Satellite Surface Finish

LAGEOS, as a totally passive satellite, has fewer constraints regarding its thermal control surface than would a satellite containing sensitive equipment. The LAGEOS satellite is to be constructed of Aluminum 6061 T6 and the following table details the overall requirements for the thermal control surface.

Table 2-3 Thermal Control Surface Requirements

1. Optical Properties

Surface	Solar Absorptance α_s	Emittance ϵ_{IR}
Satellite Exterior	0.2 - 0.5 Stable 180 days	0.05 - 1.0
Retroreflector Cavity	No Specific Values	0.05 $\pm$ 0.05

II. Reflectively Diffuse Exterior Surface

III. No Outgassing or Particulate Contamination

IV. Low Cost

Based upon the constraints of Table 2-3 several candidates were selected for closer scrutiny. These candidate surfaces are shown in Table 2-4.

Table 2-4 Candidate Surfaces

Candidate	α_s	—IR	α_s/ϵ_{IR}
Z93	0.17	0.90	0.19
Anodize (Barrier)	0.12	0.35	0.34
Anodize (Sulfuric)	0.15	0.90	0.17
Aluminum (Matte Lap)	0.52	0.29	1.8
Aluminum 6061 (Chemically cleaned)	0.16	0.06	2.7
Aluminum (Sandblasted)	0.48	0.31	1.6
Cold Plate	0.28	0.04	7.0

Careful study of the candidate surfaces of Table 2-4 resulted in the following conclusions:

1. Anodize had been considered a likely surface but final requirements indicated there was no need for this type of thermal control finish.

2. Both Z93 and gold plating were rejected based upon increased costs associated with application and handling.

None of the above candidates offered substantial advantages with respect to metal corrosion resistance. Bare aluminum 6061 T6 is a reasonably corrosion resistant surface and the cleanliness and handling requirements imposed on the satellite to prevent contamination of the retroreflectors would prevent deleterious corrosion of the bare 6061 T6. Accordingly the field of candidates was narrowed to:

1. Aluminum - Matte Lap Finish

2. Aluminum - Chemically Cleaned

3. Aluminum - Sandblasted

None of these three (3) surfaces represent the ideal finish for the LAGEOS satellite exterior surface, because:

1. A chemically cleaned surface has a good α_s value (0.16), but at low incidence angles the reflectance is not diffuse.

2. A matte lapped surface has a marginal α_s value ($\sim$ 0.5). This surface, too, lacks the ability to diffusely reflect at low incidence angles.

3. A sandblasted surface has a marginal α_s value ($\sim$ 0.5). This surface, however, diffusely reflects at all incidence angles. The major concern with this finish is the threat of particulate contamination. Particles are entrapped in the aluminum during the sandblasting operation and these may become dislodged and deposit on the retroreflectors.

Of final concern to this study was the effects of ionizing radiation on unprotected aluminum. The literature reveals that unprotected aluminum can be unstable in the presence of ionizing radiation. After consideration of the available literature data and review of the LAGEOS orbital parameters, it is concluded that the 180 day degradation of the bare aluminum should not exceed a $\Delta\alpha_s$ of 0.15 and that the most probable value of $\Delta\alpha_s$ is less than 0.1. This degradation would cause the 180 day α_s of matte lapped or sandblasted aluminum to exceed the 0.5 α_s requirement. The relative importance of the specular reflectance of chemically cleaned aluminum versus the higher α_s of the diffuse reflecting sandblasted or matte-lapped aluminum must be resolved.

Therefore, it is concluded that a bare, unprotected aluminum 6061 T6 LAGEOS satellite has a high probability of successfully withstanding the rigors of space environment. It is recommended that any combination of the following bare aluminum finishes be used on the LAGEOS satellite exterior.

1. Aluminum - Chemically Cleaned

2. Aluminum - Sandblasted

3. Aluminum - Matte Lap Finish

Practical considerations preclude the use of sandblasted and matte lap finishes on the retroreflector cavities. Consequently, it is recommended that the cavities be chemically cleaned.

It is suggested that flat 6" x 6" test panels be prepared in a manner duplicating as closely as practical the actual satellite finishes. These panels should then be optically tested.

2.7 Launch Vehicle

A Delta Launch Vehicle was chosen as the vehicle to put the LAGEOS into the desired orbit. The Delta Launch Vehicle is manufactured by McDonnell Douglas Astronautics Company and is capable of putting a satellite weighing 906 pounds, such as LAGEOS, into a 5900 km, 110 degree orbit. The three stage vehicle stands 116 feet tall with nine solid boosters attached to the first stage. The third stage has a spin table that is energized at the end of the second stage coast period which provides stability to the third stage during its burn time. An Apogee Kick Motor (AKM) inserts the LAGEOS Satellite into the desired orbit. The satellite is released in orbit at the end of the AKM burn by bolt cutters and preloaded springs employed in the spacecraft separation assembly. The spacecraft separation assembly is a part of the Delta Launch Vehicle. The launch vehicles studied for possible use for LAGEOS are shown in Figure 2-11. The 2913 vehicle has been chosen as the primary and backup launch vehicle. The launch vehicle is furnished by Goddard Space Flight Center.

2.8 Interface Definition

The LAGEOS is installed to the spacecraft separation assembly with a clampband around the equator of the satellite and four shear pins inserted into mating adapters installed in the satellite (see Figure 2-12). The clampband incorporates a leaf spring arrangement with teflon pads touching the satellite around the equator and spaced between the CCR's installed in the satellite. The clampband is preloaded when the satellite is installed by securing a bolt

LAGEOS
VEHICLE DESCRIPTION

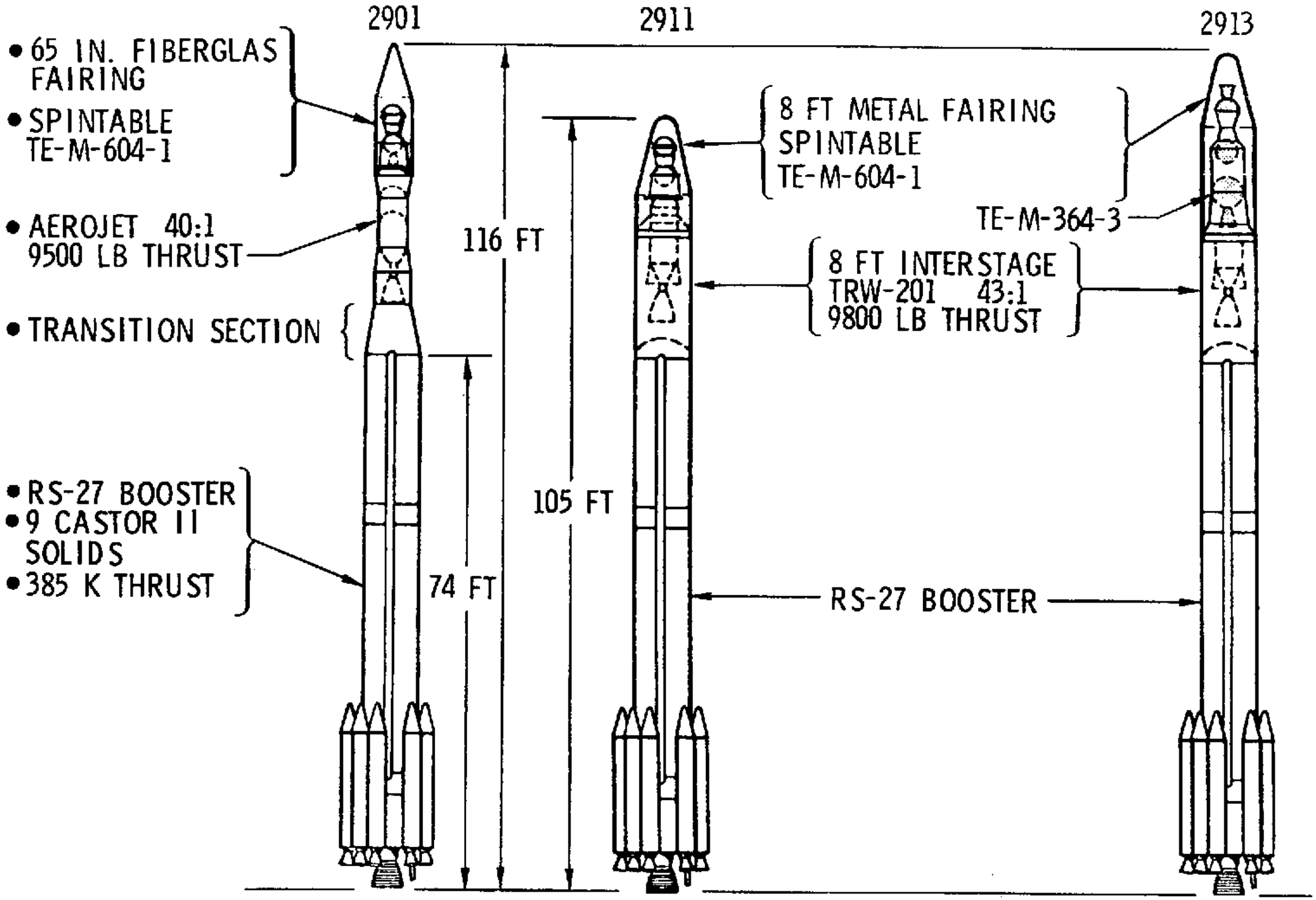


FIGURE 2-11 LAGEOS VEHICLE DESCRIPTION

LAGEOS
SPACECRAFT/CLAMPBAND INTERFACE

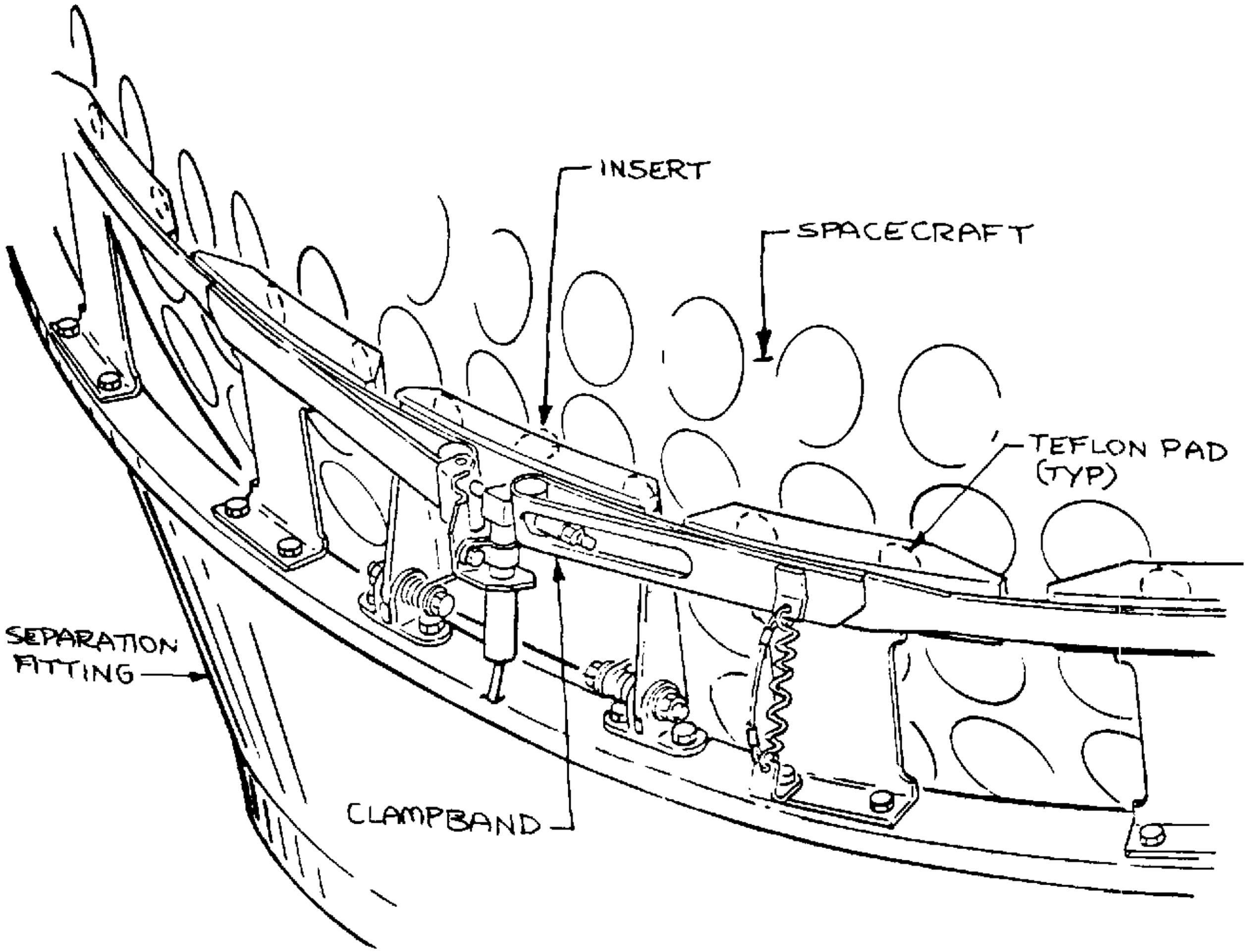


FIGURE 2-12 LAGEOS SPACECRAFT/CLAMPBAND INTERFACE

at opposite sides of the band at the shear pin locations. Four springs located beneath the satellite are preloaded to 100 pounds each to provide the required ejection force for LAGEOS and AKM separation. A cradle support, which encircles the lower CCR, provides additional stability and support during the launch phase (see Figure 2-13).

At separation command the pyrotechnic bolt cutters shear the clampband retainer bolts which allows the clampband to expand away from the satellite. The four 100 pound force springs release the satellite into orbit.

LAGEOS
SEPARATION SYSTEM

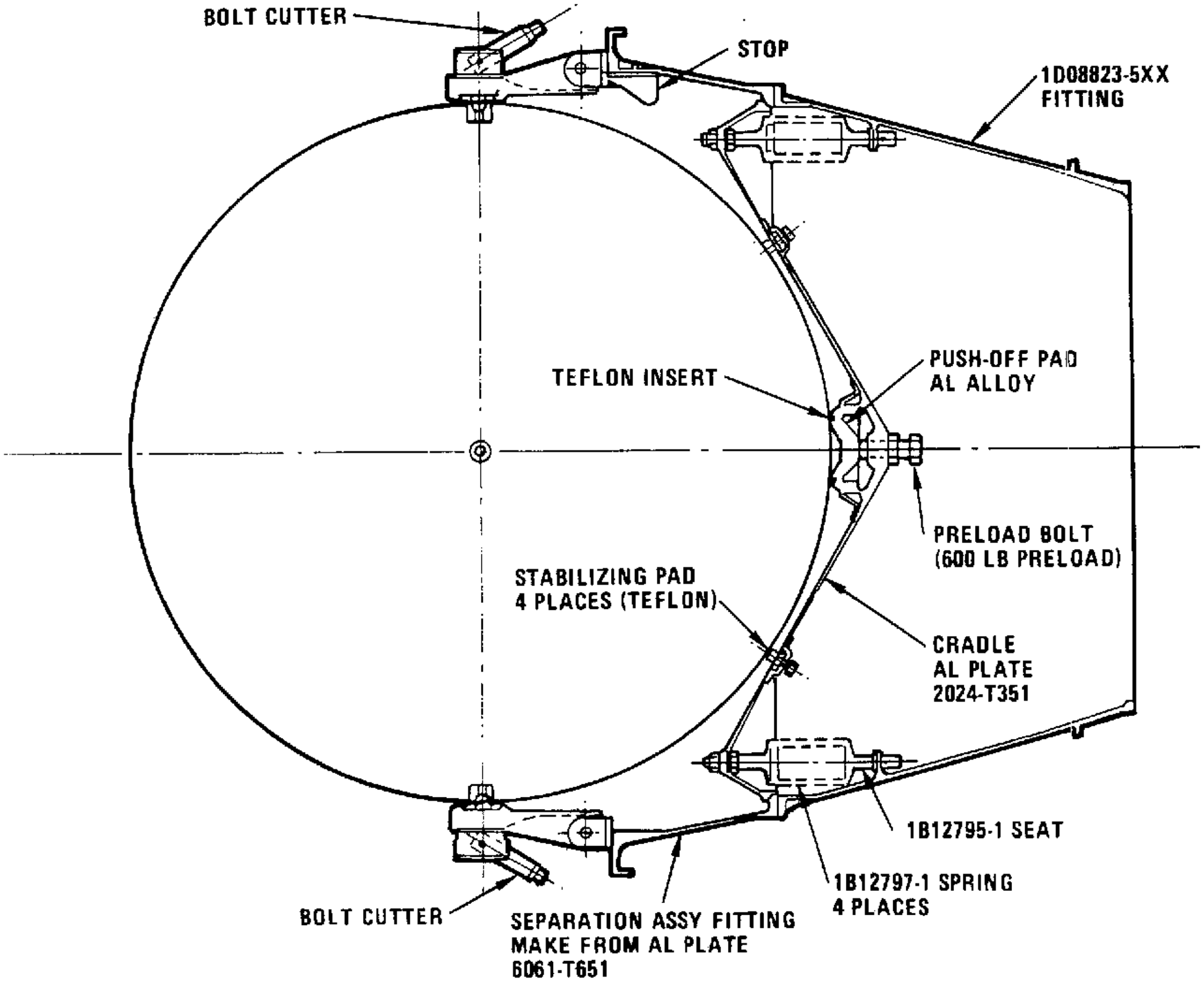


FIGURE 2-13 LAGEOS SEPARATION SYSTEM

3.0 Thermal Considerations

3.1 Thermal Summary

Thermal design of the LAGEOS satellite was based on maintaining the cube corner retroreflectors (CCR's) at a constant temperature to optimize optical performance. This is accomplished by isolating the CCR's both conductively and radiatively from the satellite core. The ALSEP data indicated that CCR temperature gradients below 2^oC would yield acceptable optical performance. Subsequently, this temperature requirement was replaced with the requirement that the optical performance of the CCR's should not be degraded by more than 50 percent due to CCR temperature gradients.

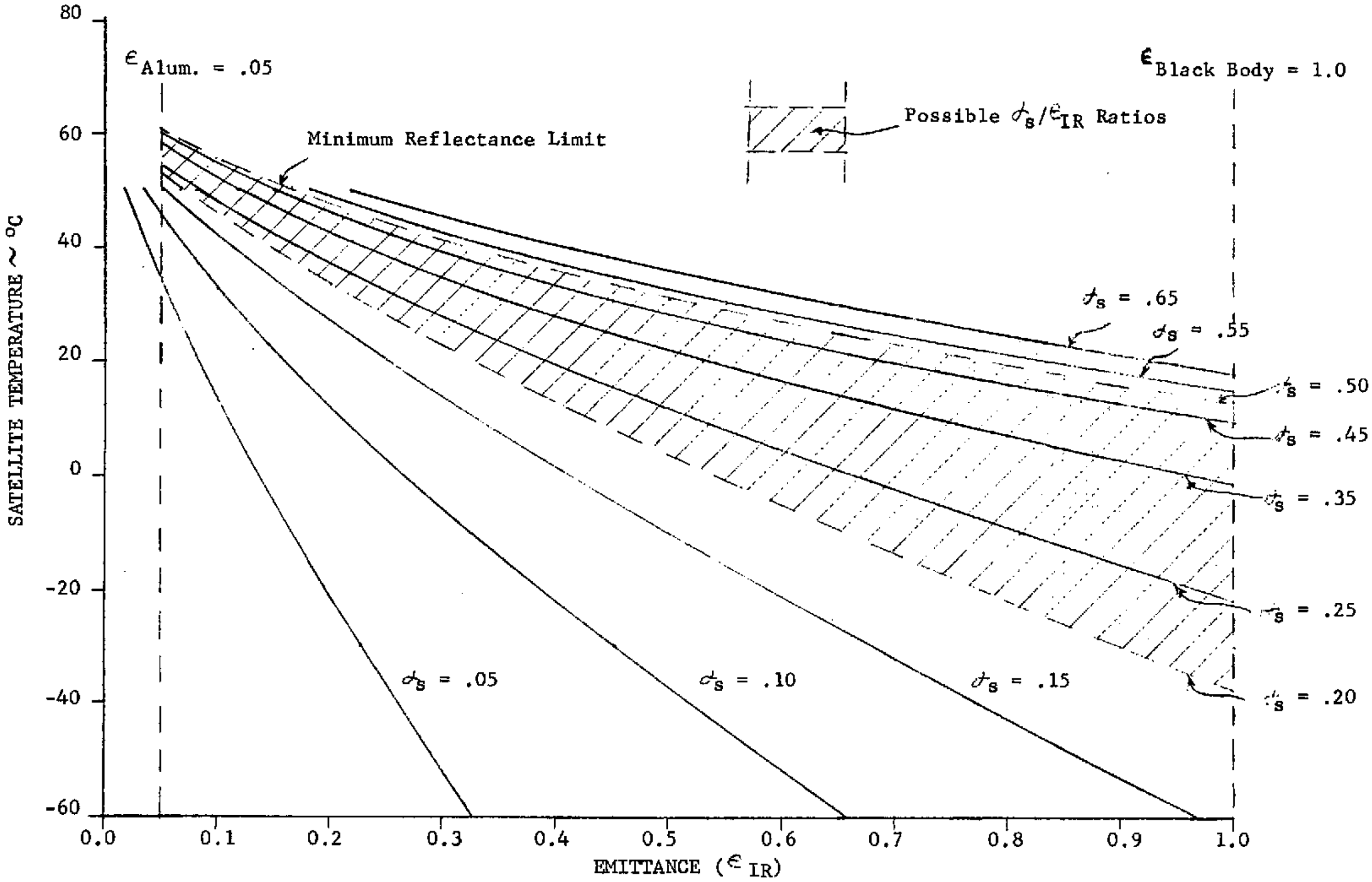
Thermal models of the satellite and CCR's developed by MSFC and Bendix were used to define the worst case thermal design environments. The range of expected satellite temperatures was calculated based upon the maximum and minimum solar absorptance to infrared emittance (α_S/ϵ_{IR}) ratios expected for various satellite surface coatings/finishes. The resulting CCR temperature gradients were supplied to Itek for use in the optical analyses. The maximum and minimum predicted satellite temperatures combined with solar and infrared heating loads were imposed on six CCR's at Bendix to determine if the optical performance degradation was less than 50 percent. Test results also defined the thermal considerations for selection of optical properties of the satellite exterior surface and mounting cavity. Correlation of the test data with the thermal models verified the mounting and retainer ring design and demonstrated that the models can be used for orbital performance predictions.

3.2 Thermal Design Environment

The LAGEOS will be launched into a 110° inclination 5900 Km altitude circular orbit. Maximum solar, albedo and planetary infrared heating rates are 1412.5, 38.1, and 66.5 watts/meters^2, respectively. The maximum eclipse time will be 39 minutes (17 percent of the orbit). Information from aerodynamics studies showed that due to its metallic content, the satellite would spin down from its initial 90 RPM to nearly no spin in less than one year. In addition, no preferred spin axis could be defined. Therefore, a hemisphere of the LAGEOS will be receiving solar heating for most of its orbit. The no spin condition in combination with various solar absorptance, α_s, and infrared emittance, ϵ_{IR}, values for the satellite exterior surface was used to define the expected range of satellite temperatures as shown in Figure 3-1. A minimum reflectance limit of 0.50 is required for optical tracking. Possible infrared emittance ϵ_{IR} values range from 0.05 for bare machined aluminum up to 0.90 for certain paints (Z-93 and S-13G are examples). Possible solar absorptance α_s, values also range from 0.20 up to 0.90. Absorptance degradation that occurs for most coatings/finishes is difficult to predict. Therefore, the design temperature extremes were defined by the lowest and highest possible temperatures shown in Figure 3-1. These temperatures are -30°C and +60°C, respectively.

For thermal design purposes, it was assumed that the cube corners of interest at any moment (those returning an incident laser beam) could be irradiated by a combination of the following heat loads: (1) no solar and no infrared heat; (2) solar and no infrared heat: (3) infrared and no solar heat and (4) both solar and infrared heat. The first three combinations of heat environments on the CCR's were tested at Bendix.

FIGURE 3-1 LAGEOS - SATELLITE TEMPERATURE VERSUS SURFACE EMITTANCE - NO SPIN CASE



The cavity which surrounds each CCR has the greatest influence on temperature gradients in the CCR's. As shown in Figure 3-2, for a satellite temperature of +30°C with no solar or infrared heat loads, increasing the cavity emittance from 0.05 to 0.90 increases the axial CCR gradient from 2.06°C to 4.04°C. Axial and radial CCR temperature gradients both increase with increasing satellite (cavity) temperature. Radial gradients are generally 10 to 20 percent of the axial gradients. The Kel-F (chlorotriflouroethylene, CTFE) mounting rings were designed to allow free movement of the CCR's and minimize contact conduction. In addition, the conductivity of Kel-F, 4.292 (10^{-6}) watts/M-$^\circ$C, is low. The retainer ring serves as a thermal insulating barrier for the Kel-F upper ring by blocking solar and infrared heating and introducing a contact resistance interface.

Recession of the CCR's into the mounting cavities creates a cavity around the CCR front face. The view factor from the front face to space is reduced with increasing recession depth and hence the energy radiated from the front face is reduced. This results in higher front face temperatures and lower gradients. The effects of increasing the recession depth/cavity diameter ratio, variations of satellite temperature, cavity emittance and CCR infrared heat loads are presented in Figure 3-3. Increasing infrared heating reduces temperature gradients because the energy is absorbed at the front face and the front face temperature is increased.

FIGURE 3-2. CCR TEMPERATURE GRADIENTS VERSUS SATELLITE TEMPERATURE

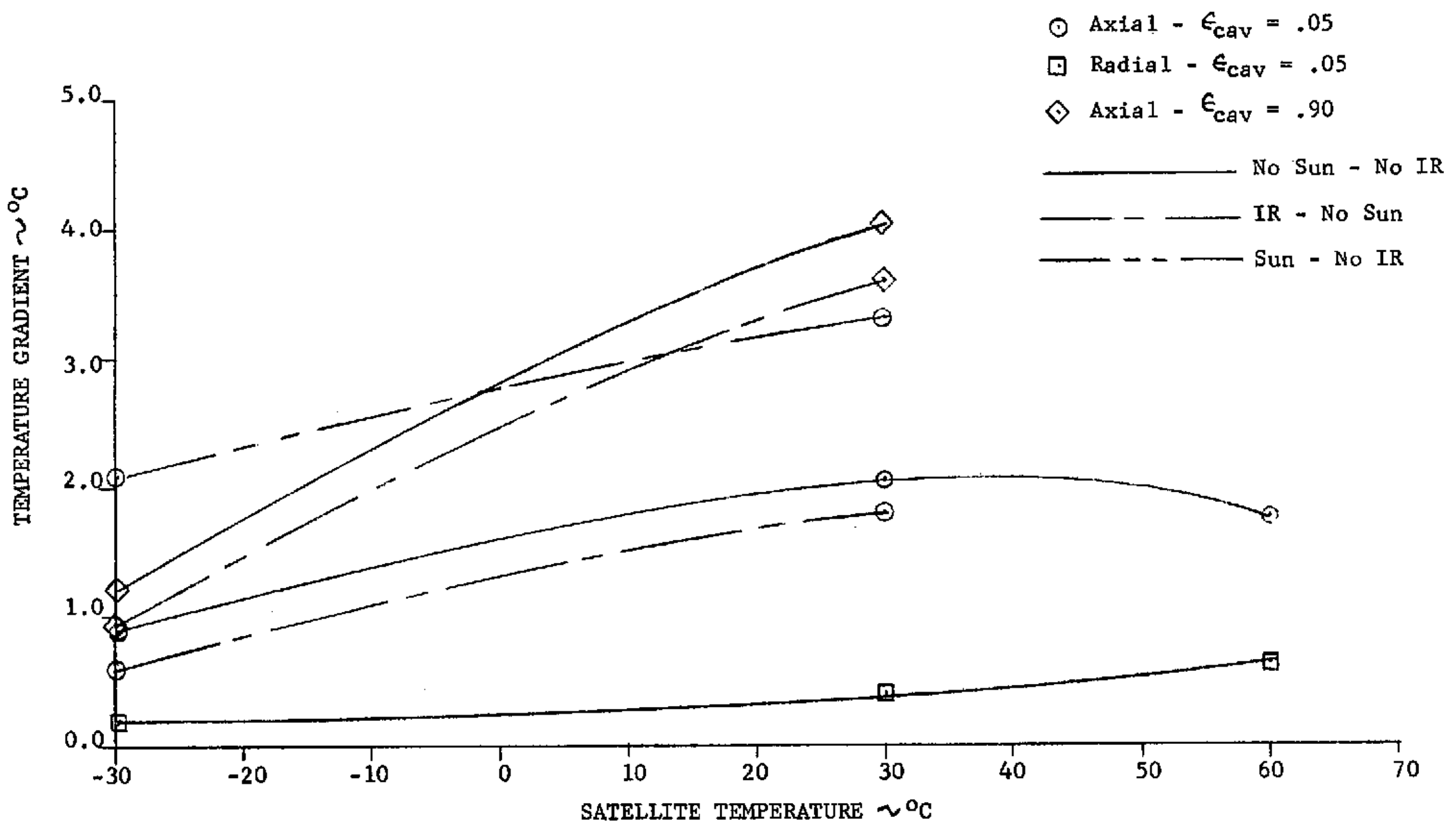
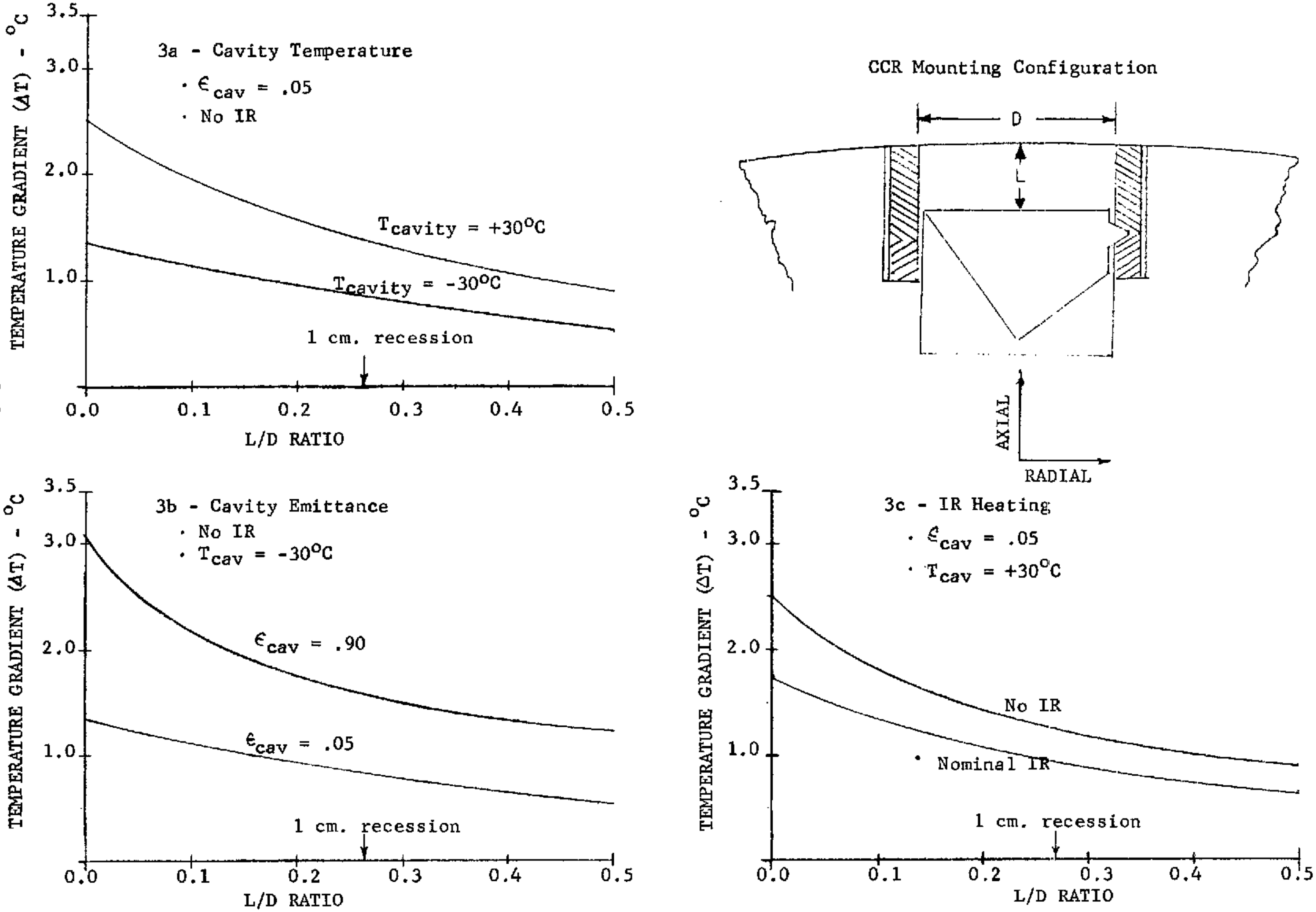


FIGURE 3-3 CCR AXIAL GRADIENT VERSUS RECESSION DEPTH, CAVITY TEMPERATURE, CAVITY EMITTANCE, AND IR HEATING



Analysis showed that a maximum transient temperature gradient between the two hemispheres is 10°C. This was based upon two worst case assumptions: (1) the solar heating terminator coincides with the hemisphere interface equator line; and (2) heat is only conducted between the hemispheres at the bolt interfaces. Temperature gradients between the hot and cold sides of the LAGEOS sphere will be less due to the small probability that this particular solar heating condition will occur for extended periods of time. Additionally, there will be some heat conduction across the hemisphere intersection area.

Transient variation of the average satellite temperature is also minimal (as shown in the Bendix Phase B Report No. BSR 4159). The LAGEOS in orbit will approach a nearly steady state temperature within a few days time. Variation (increase) of this temperature due to satellite exterior optical property degradation will be gradual.

3.3 Thermal Model Development and Test Predictions/Correlation

The MSFC thermal models will be described in the following paragraphs of this section. A description of the Bendix thermal model is included in the Bendix Report No. BSR 4159. MSFC thermal models are steady state models of one CCR and cavity, whereas, the Bendix models are primarily transient models of the satellite and CCR's.

An eight node model of a sphere (one node for each octant) was initially used to obtain solar, albedo, and earth infrared LAGEOS heating rates. The CCR steady state model consisted of 66 nodes and approximated the CCR by a cone. This model was used to examine the effects of the parameter variations shown in Figure 3-3. A typical output from this model is shown in Figure 3-4. A comparison between MSFC and Bendix pretest CCR temperature predictions and the actual test temperatures is shown in Table 3-1.

These models were verified by the close correlation with test results as shown in Table 3-2. The only adjustments to the pretest analysis were lowering the volumetric absorption by the CCR's of solar heat and the retainer ring solar absorptance. The Bendix model was used to calculate input temperature gradients for Itek optical analyses . Table 3-3 presents a summary of the thermally perturbed cases for the optical analyses. These cases were representative of the maximum expected CCR temperature gradients.

FIGURE 3-4. TYPICAL 66 NODE THERMAL MODEL OUTPUT

```
   I                   LAGEOS - CCR 66 NODE THERMAL MODEL - CASE NO.  1
-30.00
   I                      Cavity Temperature = -30°C
   I                      εcav = 0.90
   I                      No Recession
   I
   I ************************************************************************
   I *
   I *-57.09  -57.10  -57.11  -57.10  -57.09  -57.09  -57.10  -57.11  -57.10  -57.0
   I *
   I *
   I *-56.63  -56.64  -56.66  -56.66  -56.65  -56.65  -56.66  -56.66  -56.64  -56.6
   I *
   I *
   I *-56.15  -56.20  -56.23  -56.25  -56.24  -56.24  -56.25  -56.23  -56.20  -56.1
   I *
   I  *
   I  -55.60  -55.75  -55.83  -55.85  -55.84  -55.84  -55.85  -55.83  -55.75  -55.6
   I    *                                                                         *
   I     *                                                                       *
   I     -55.36 -55.53 -55.61 -55.65 -55.63 -55.63 -55.65 -55.61 -55.53 -55.36
   I        *                                                                 *
   I         *                                                               *
   I         -55.1 -55.3 -55.4  -55.4 -55.4 -55.4 -55.4  -55.4 -55.3 -55.1
   I           *                                                         *
   I            *                                                       *
   I             *     -55.05     -55.18     -55.17      -55.14      -54.89
-30.00             *                                                  *
   I                *                                                *
   I                 *   -54.79   -54.92    -54.90    -54.88    -54.66
   I                  *                                               *
   I                   *                                             *
   I                    *  -54.53 -54.63    -54.61  -54.60  -54.41 *
   I                     *                                        *
   I                      *                                      *
   I    -                  *                                    *   I---------I
   I    I                    -54.2 -54.3 -54.3 -54.3 -54.2
   I    I AXIAL GRADIENT MAX. *                            *   RADIAL GRADIENT MAX.
   I    I                      *                          *
   I    I  1 61      4.0785     *                        *     36 40        0.2861
   I    I                        * -54.0  -53.93  -53.86
   I    I AXIAL GRADIENT MIN.     *                    *       RADIAL GRADIENT MIN.
   I    I                          *                  *
   I    I  5 65      4.0447         *                *          1  5        0.0415
   I    I                            -53.5-53.5-53.5
   I    -                              *          *
   I                                   -53.1 -53.05
   I                                     *      *
   I                                      -53.01
   I                                       *  *
-30.00                                       *
   I
   I
   I
   I
   -----------------------------------------------------------------------------
```

TABLE 3-1: COMPARISON OF LAGEOS PREDICTIONS/TEST DATA

ENVIRONMENTAL CONDITIONS	CAVITY TEMP	BENDIX ANALYSIS CCR FACE	BENDIX ANALYSIS RETAINER RING	MSFC ANALYSIS CCR FACE	MSFC ANALYSIS RETAINER RING	T/V TEST CCR FACE	T/V TEST RETAINER RING
No Sun, No IR	-30.0°C	-64.5°C	-38.2°C	-70.7°C	-42.9°C	-62.5°C	-36.0°C
No Sun, IR	-30.0°C	-51.7°C	-35.5°C	-54.6°C	-39.7°C	-47.0°C	-33.5°C
Full Sun, No IR	-30.0°C	-34.7°C	+ 7.2°C	-33.2°C	+25.6°C	-43.5°C	-17.0°C
No Sun, No IR	+30.0°C	-20.9°C	+12.4°C	-26.5°C	+ 4.3°C	-23.5°C	+21.0°C
No Sun, IR	+30.0°C	-12.1°C	+14.9°C	-16.4°C	+ 7.0°C	-13.5°C	+21.5°C
Full Sun, No IR	+30.0°C	+ 2.8°C	+51.3°C	+ 0.6°C	+61.7°C	-20.0°C	+21.5°C

TABLE 3-2. POST-TEST THERMAL ANALYSIS AND TEST CORRELATION (TEST ARTICLE)

		T/V TEST		BENDIX ANALYSIS		MSFC ANALYSIS	
ENVIRONMENTAL CONDITION	CAVITY TEMP	CCR FACE	RETAINER RING	CCR FACE	RETAINER RING	CCR FACE	RETAINER RING
Full Sun, No IR	-30.0°C	-43.5°C	-17.0°C	-50.8°C	-18.6°C	-44.2°C	-9.47°C
Full Sun, No IR	+30.0°C	-20.0°C	+21.5°C	-10.1°C	+29.1°C	- 9.6°C	+31.9°C
No Sun, No IR	+60.0°C	-1.0°C	+38.0°C	+1.0°C	+36.5°C	-10.4°C	+24.5°C

1. RETROREFLECTOR VOLUMETRIC SOLAR ABSORPTANCE MODIFIED FROM 5.0% to 2.5%.
2. SOLAR ABSORPTANCE OF BARE, MACHINED ALUMINUM MODIFIED FROM 37% to 15%.
3. ALL OTHER LAGEOS THERMAL ANALYSIS ASSUMPTIONS REMAIN UNCHANGED.

TABLE 3-3. RETROREFLECTOR TEMPERATURE GRADIENT INPUT TO ITEK AND COMPUTED OPTICAL RETURN

ITEK CASE NUMBER	CCR Δ T AXIAL	CCR Δ T RADIAL	% RETURN IN ANNULUS (32-41μ Rad. Radii)	DESCRIPTION
2.1	0.0°C	0.0°C	18.4	PERFECT 1.5" CUBE AT 25°C
2.3.b 2.4.b.2	1.9°C	1.3°C	17.2	BARE, MACHINED, 6061-T6 ALUMINUM RETAINER RING AND SATELLITE: + 30°C CAVITY; FULL SUN; NO IR.
2.3.a.1	1.0°C	0.4°C	18.0	Z-93 COATING ON RETAINER RING AND SATELLITE EXTERIOR SURFACE; BARE, MACHINED ALUMINUM CAVITY AT -30°C; FULL SUN; NO IR.
2.3.a.2	3.5°C	2.0°C	17.1	ESTIMATED MAXIMUM RETROREFLECTOR TEMPERATURE GRADIENTS
2.5.a	2.0°C	0°C	15.9	HYPOTHETICAL AXIAL TEMPERATURE GRADIENT
2.5.b	0°C	2.0°C	4.2	HYPOTHETICAL RADIAL TEMPERATURE GRADIENT

3.4 Thermal/Vacuum Test Results

The purpose of the LAGEOS Phase B thermal/vacuum tests was to subject six CCR's using one mounting method, to the worst case predicted thermal environments. The temperature extremes (-30°C to +60°C) were representative of the range of expected satellite exterior coating/finish optical properties. The objective of the tests was to demonstrate that the imposed CCR temperature gradients would not reduce optical return by more than 50 percent. Additionally, the effects of the launch vibration environment on thermal performance were investigated.

A complete description of the test article, thermocouple locations and test conditions is included in the Bendix Report. The test corner cubes were assumed to be at the same temperatures as the ALSEP cubes mounted in the thermocouple fixture. Combinations of the solar and infrared heating conditions were imposed on the test article cubes. The combined solar and infrared heating case was not run because of the difficulty in calibrating both heat sources at the same time. The solar tests at -30°C and +30°C showed that the volumetric absorption of solar energy by the CCR's was approximately 2.5% as opposed to the pretest prediction of 6%. Off-normal solar cases were not run because of the low CCR volumetric solar absorption.

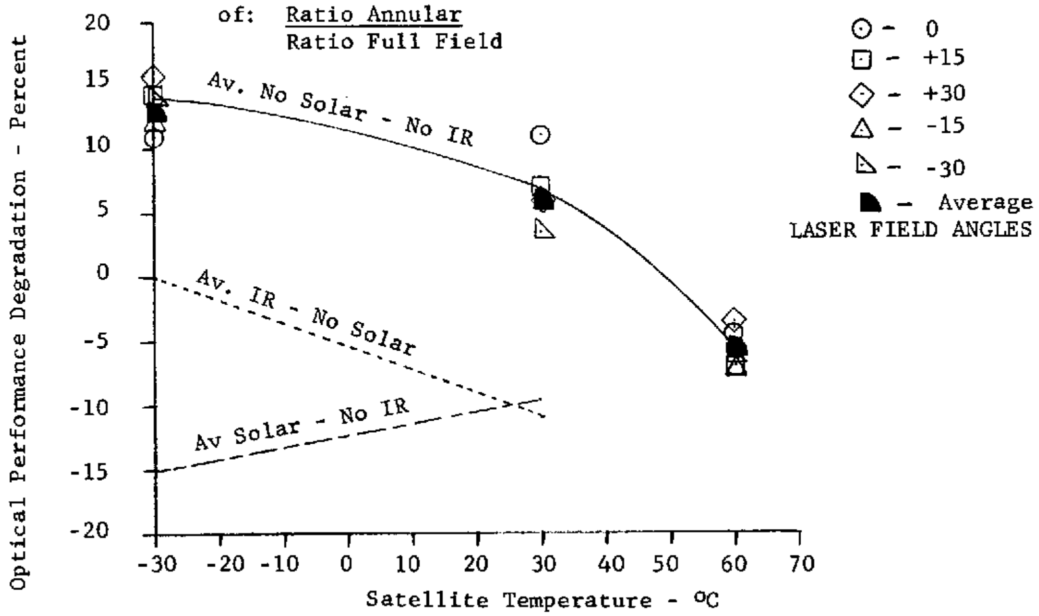
The measured CCR front face temperatures were close to pretest predictions. The apex and tab temperatures were not representative since the thermocouples were not insulated from viewing the cavity wall. Temperature gradient data was not useful for absolute values. However, the gradient measurements were used to determine when stable equilibrium conditions had been attained. Confidence in the predicted gradients was maintained due to the close agreement between predictions and test data for the front face thermocouples.

Optical performance was degraded less than 50 percent due to CCR temperature gradients in all thermal tests. The average degradation was less than 20% as shown in Figure 3-5. Less degradation was shown in most cubes and for most polarizations when the test article (satellite) temperature was increased.

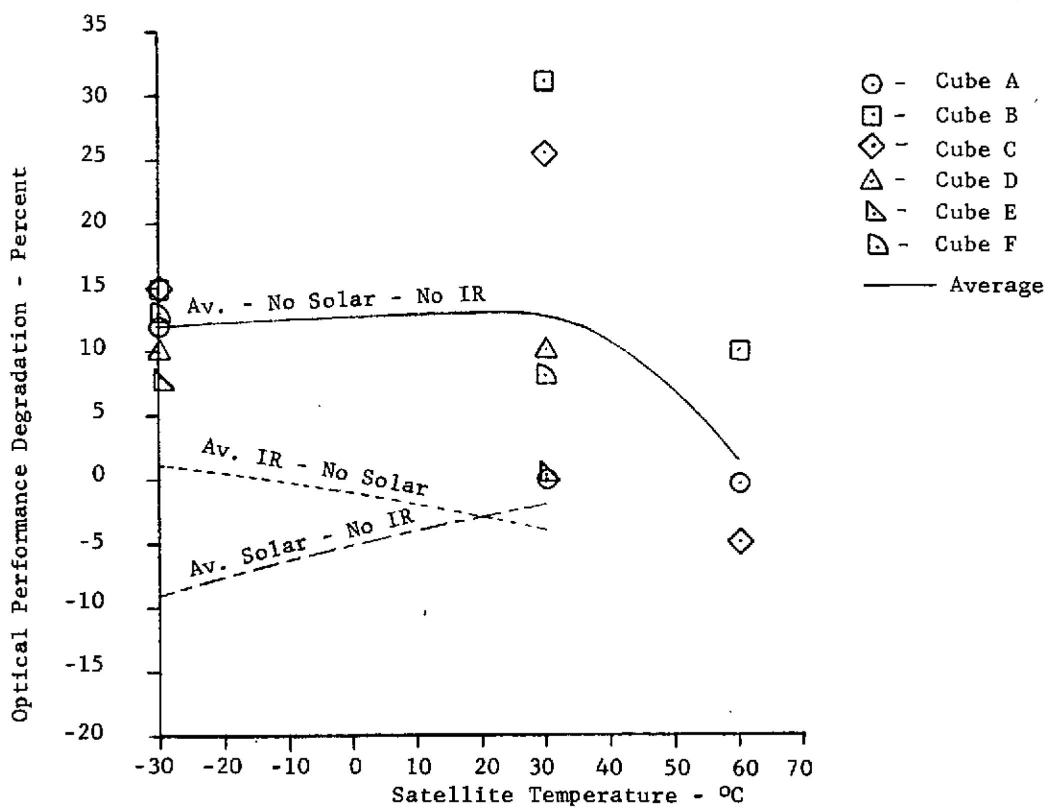
Thermal performance of the mounting and retainer rings was not degraded by the vibration tests. Cube corner and ring temperatures were almost identical before and after the vibration tests. Post-test measurements of the test article optical properties showed that the solar absorptance, α_S was 0.26 and the infrared emittance ϵ_{IR} was 0.06.

FIGURE 3-5. OPTICAL PERFORMANCE DEGRADATION VERSUS SATELLITE TEMPERATURE

8a. Return Summed Across all Polarizations using Ratio of: Ratio Annular / Ratio Full Field



8b. Return for Six Cubes at 0 Degree Field Angle



3.5 Thermal Conclusions and Recommendations

Conclusions from the Phase B analyses and tests are:

1. Isothermal optical performance is degraded by CCR temperature gradients. Optical performance degradation was less than 50 percent in all thermal tests.

2. Optical performance degradation was less at higher cavity (satellite) temperatures.

3. The vibration tests did not alter CCR mount thermal performance.

4. The proposed mounting/retainer rings provide adequate thermal control for the CCR's.

5. There is good agreement between test data and thermal model predictions and confidence in flight predictions using these models.

Recommendations for the LAGEOS design are:

1. Mounting cavity infrared emittance, ε_{IR} should be 0.05 + 0.05.

2. Thermal considerations should be low in priority for satellite exterior surface coating/finish selection.

4.0 OPTICAL ANALYSIS AND TEST

4.1 OPTICS CONSIDERATION AND PURPOSE:

The LAGEOS satellite orbital parameters establish the velocity aberration angle between the transmitted and reflected laser beam. Geometrical calculations establish these limits to be between 6.6 and 8.45 arc seconds off-axis or within an annulus from 13.2 to 16.9 arc seconds. The Phase B Study was designed to theoretically predict and experimentally measure the energy in this area of the far field diffraction pattern (FFDP).

The testing and analyses were to be performed on a series of CCR's manufactured to the Level I NASA Headquarters specification. These were:

a. Material - T19 Suprasil I Special (fused silica).

b. Refractive index homogeniety - 1×10^{-6}/cm.

c. Coatings - none.

d. Dihedral angles - $90^{\circ}\ 0'\ 1.5'' \pm 0.5''$.

e. Surface quality - reflected beam $\lambda/4$ (Pk - Pk) across each of the six (6) faces.

f. Front face shape - circular.

g. Diameter ≈ 3.8 cm.

The satellite was to have a reflectance, in the area not covered by retroreflectors, equal to that obtained from clear annodized aluminum and this area must be equal to at least 30% of the satellite surface.

The optical performance of the CCR's under worst case thermal loading was to be no worse than 1/2 that measured for an isothermal cube.

4.2 CCR CONFIGURATION STUDY: An early portion of the study dealt with the possible use of a hexagonal instead of the circular CCR. The rationale for this suggestion was the anticipated cost differential between the manufacture of the hexagonal vs circular cubes. As the analysis progressed, it was discovered that present tooling and manufacturing techniques had equalized the cost between cubes. A proven mount concept for the circular cube existed from the ALSEP program, thermal analysis indicated the circular mount would perform better than the hexagonal mount and the circular cube would be easiest to model; so the circular cube was selected as best satisfying the LAGEOS requirements.

4.3 OPTICAL ANALYSIS: The optical analysis was then designed to produce predicted optical performance for the LAGEOS CCR's under isothermal and various thermal gradient conditions for comparison with thermal/optical test results. These results would demonstrate that optical performance predictions could be generated for the LAGEOS CCR's under various orbital conditions. This data could then be used to support future LAGEOS satellite system operations.

Optical energy distribution and integrated intensity was determined for the 13.2 to 16.9 arc second annulus of the FFDP by Fourier transformation of the optical-path-differences (OPD's). These OPD's were calculated from the variables in the CCR parameters and included: (a) retroreflector geometry, (b) index of refraction of the material, (c) coefficient of expansion of the material, (d) laser wavelength, (e) manufacturing irregularities in the angles between the reflecting faces, (f) surface irregularities, (g) aperture geometry and (h) thermal perturbations. This optical return intensity profile could be directly interpreted to establish the theoretical CCR optical performance.

The optical analysis, Table 4-1, indicates several facts: (a) The CCR's are not severely affected by $\lambda/4$ wavefront errors and random $\pm$ 0.5 arc second dihedral angle errors, (b) a CCR manufactured with 90° 0' 2.1" angles instead of 90° 0' 1.5 " angles suffers a large amount of performance degradation and (c) anticipated temperature gradients do not severely impact the CCR optical performance.

Table 4-1

OPTICAL ANALYSIS RESULTS

ΔTa = Axial Temperature Gradient
ΔTr = Radial Temperature Gradient
* Energy in The Far Field Diffraction Pattern Between 32 and 42 Microradians
** Dihedral Angle is 90° Plus Value Shown

Dihedral Angles **	Temperature Gradient	Wavefront Error (P-P)	Laser Field Angle	% Energy Return *
1.5", 1.5", 1.5"	Isothermal	0	0°	18.4
1.5", 1.5", 1.5"	Isothermal	0	15°	9.6
1.5", 1.5", 1.5"	Isothermal	λ/4	0°	18.0
1.5", 1.5", 1.5"	Isothermal	λ/4	15°	8.8
1.0", 1.5", 2.0"	Isothermal	λ/4	0°	17.7
1.0", 1.5", 2.0"	Isothermal	λ/4	15°	8.6
1.5", 1.5", 1.5"	ΔTa = 1.0° C, ΔTr = 0.4°C	λ/4	0°	18.0
1.5", 1.5", 1.5"	ΔTa = 3.5° C, ΔTr = 2.0°C	λ/4	0°	17.1
1.5", 1.5", 1.5"	ΔTa = 1.9° C, ΔTr = 1.3°C	λ/4	0°	17.2
1.5", 1.5", 1.5"	ΔTa = 1.9° C, ΔTr = 1.3°C	λ/4	15°	8.3
1.0", 1.5", 2.0"	ΔTa = 1.9° C, ΔTr = 1.3°C	λ/4	0°	16.9
1.0", 1.5", 2.0"	ΔTa = 1.9° C, ΔTr = 1.3°C	λ/4	15°	8.1
1.5", 1.5", 1.5"	ΔTa = 2.0° C, ΔTr = 0.0°C	λ/4	0°	15.9
1.5", 1.5", 1.5"	ΔTa = 0.0° C, ΔTr = 2.0°C	λ/4	0°	4.2
2.1", 2.1", 2.1"	Isothermal	0	0°	13.2
2.1", 2.1", 2.1"	Isothermal	λ/4	0°	11.8
2.1", 2.1", 2.1"	ΔTa = 1.9° C, ΔTr = 1.3°C	λ/4	0°	10.9
2.1", 2.1", 2.1"	ΔTa = 2.4° C, ΔTr = 1.5°C	λ/4	0°	12.3
1.6", 2.1", 2.6"	Isothermal	λ/4	0°	12.1
1.6", 2.1", 2.6"	Isothermal	λ/4	0°	11.1
2.1", 2.1", 2.1"	ΔTa = 2.0° C, ΔTr = 0.0°C	λ/4	0°	17.6
2.1", 2.1", 2.1"	ΔTa = 0.0° C, ΔTr = 2.0°C	λ/4	0°	1.1

4.4 OPTICAL TESTING

The purpose of the test program was to experimentally determine the thermal/optical performance of the LAGEOS Satellite CCR's and mount design under orbital worst-case thermal vacuum conditions and after exposure to satellite vibration qualification levels.

The tests were performed at the Bendix Aerospace Division at Ann Arbor, Michigan, in an arrangement similar to that shown in Figure 4-1 and at MSFC in a similar arrangement. The CCR's were mounted inside a thermal vacuum chamber on a device which can rotate them through a 180° arc. In one attitude the test articles are looking at devices which simulate various environmental conditions. After they reach a steady state condition, they are rotated 180° to a position where they can be measured by the far field diffraction instrument (FFDI).

The CCR's are placed in the test mount as shown in Figure 4-2. The mount has cavities for attaching six (6) CCR's and has the capability of maintaining the desired environmental condition for an extended period of time. To insure that test conditions remain stable a series of thermocouples, installed in various positions throughout the mount, continually monitor temperature fluctuations. If previously established limits are exceeded the test is interrupted, and the CCR's are rotated back to expose them to the devices simulating the desired environmental conditions.

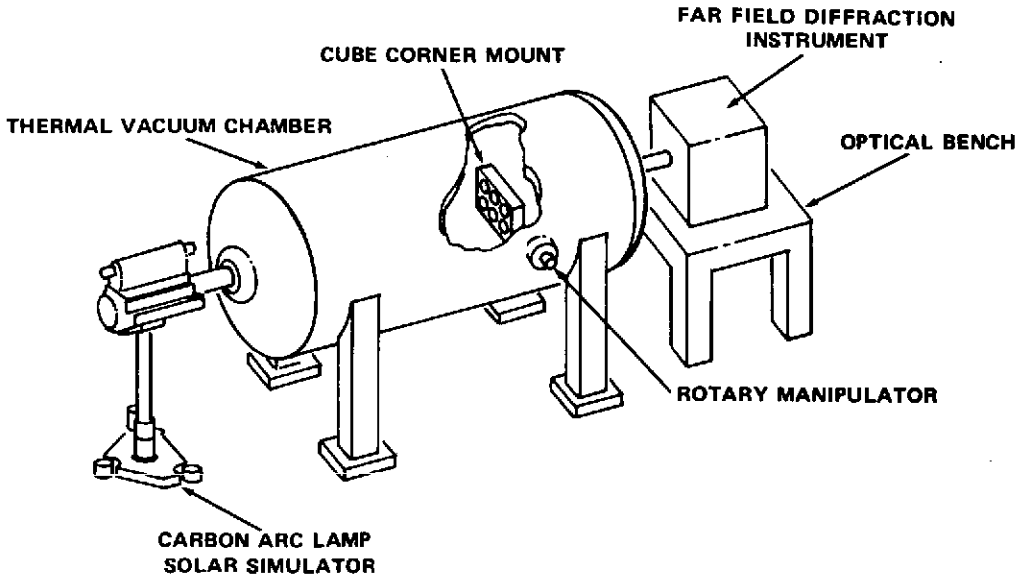


FIGURE 4–1. THERMAL/OPTICAL TEST SET-UP

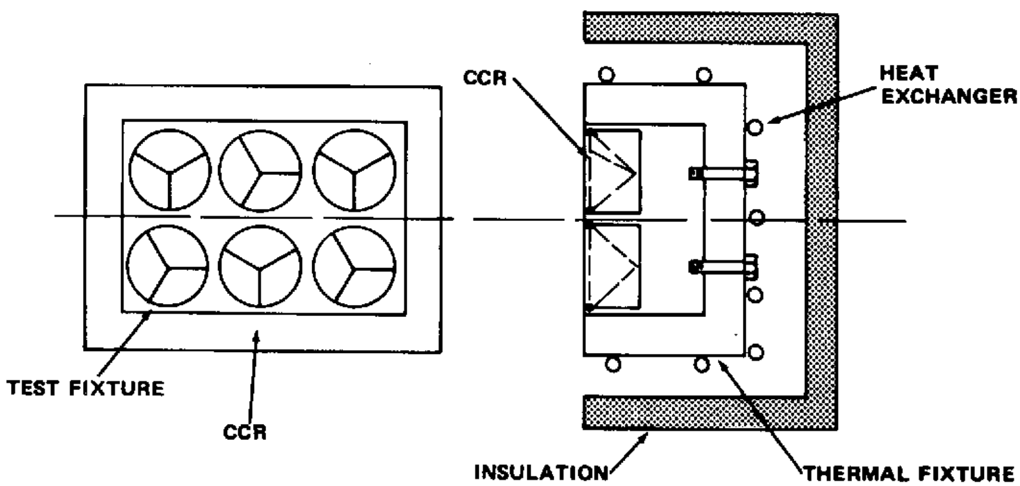


FIGURE 4–2. LAGEOS RETROREFLECTOR TEST MOUNT

Figure 4-3 gives a more detailed view of the translation and rotation device. During any test sequence, any of the three (3) CCR's on the rotation axis of the manipulator can be examined by the FFDI. Because all six (6) CCR's can not be measured at one time, a series of tests are performed on three (3) cubes, the test mount is then removed, turned over, and re-installed and the test sequence is performed on the other three (3) CCR's.

Figure 4-4 depicts the FFDI. This device was built specifically to measure the far field diffraction patterns (FFDP) produced by CCR's and was purchased to perform the LAGEOS Phase B study. Its salient features are:

a. A HeNe laser light source operating at 6328Å.

b. A beam diameter of 50 mm with a uniformity of less than 15% variation across the beam.

c. The emitted wavefront quality will be better than $\lambda/10$.

d. To provide either circular polarization, or linear polarization with the E-Vector rotated to any plane.

e. Three output measurement channels.

The measurement channels are:

a. A view screen providing a FFDP display of 75 arc seconds diameter.

b. A photographic channel containing a polaroid camera to take pictures of a FFDP of 75 arc seconds diameter.

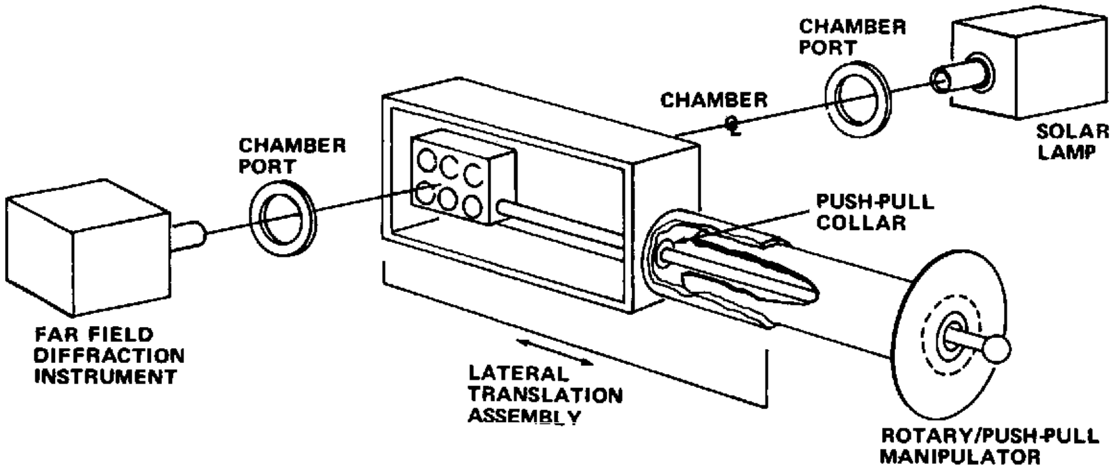
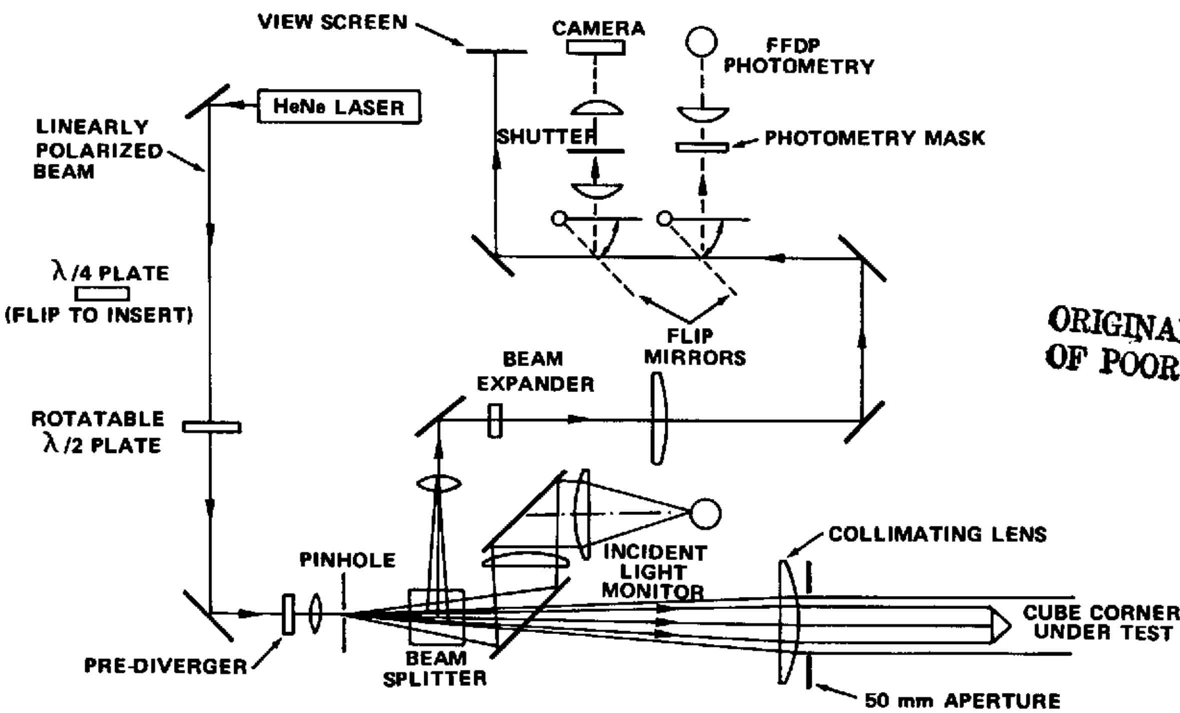


FIGURE 4–3. THERMAL VACUUM CHAMBER MANIPULATOR



ORIGINAL PAGE IS
OF POOR QUALITY

FIGURE 4–4. FAR FIELD DIFFRACTION INSTRUMENT OPTICAL SCHEMATIC

c. A photometric channel which can measure one of three quantities:

1. Incident light monitor which measures the laser light unused by the 50 mm beam.

2. Return light monitor which measures the light reflected by the CCR. A mask holder provided in this channel permits the selection of a 107.5 arc second diameter FFDP, or any portion of it, to be measured.

3. A ratio, of the incident light to the return light, monitor.

Four masks were manufactured for the FFDI. These were:

a. An annulus of 13.2 to 16.9 arc seconds diameter, which spans the entire spectrum of velocity aberration angles anticipated for the LAGEOS satellite.

b. A full field of 107.5 arc seconds diameter which intercepts all the light reflected by the CCR.

c. A half annulus of 15.2 to 16.9 arc seconds diameter which provides a method to compare the return beam power at lower velocity aberration angles to that received at higher velocity aberration angles.

d. A 60° segment of a full field of 107.5 arc seconds which when inserted with an annulus mask permits the determination of the return beam intensity in any 60° segment of the annulus.

Measurements made and recorded during most of the test sequence were:

a. Incident light.

b. Return light intensity in the FFDP annulus.

c. Ratio of the annular return light to the incident light.

d. Ratio of the full field return light to the incident light.

A special test was performed at an isothermal vacuum condition to measure the energy contained in the inner and outer 1/2 of the annulus and the energy in 60° segments of the 13.2 to 16.9 arc second diameter annulus. The performance ratio for the cube was calculated from measurements c. and d. ; (ratio-annular @ α)/(ratio-full field @ $\alpha = 0^\circ$) and because the ratio measurements were used, the fluctuations in the laser output intensity could be disregarded.

The reference parameters recorded during the test sequence are defined in Figure 4-5. θ is the angle the reference CCR edge makes with respect to the incident polarization. α is the angle of incidence the impinging light makes with the front face.

Six (6) CCR's were manufactured for the test. These articles were manufactured to the LEVEL I NASA Headquarters specifications. Their as manufactured parameters are listed in Table 4-2. The CCR's were mounted into the test fixture as shown by Figure 4-6. Configuration 1 was used only during Test 1, configuration 3 was used for all post vibration tests, and configuration 2 was used for all other tests (Table 4-3).

Table 4-2

LAGEOS PHASE B TEST CCR PARAMETERS

TEST LOCATION	A	B	C	D	E	F
SERIAL NO.	3	5	6	1	4	2
WAVEFRONT DEVIATION	FRACTIONS OF WAVELENGTH AT 6328A° (PK - PK)					
SECTOR 1	.15	.10	.10	.20	.20	.20
2	.15	.20	.12	.15	.10	.15
3	.10	.10	.10	.10	.20	.17
4	.10	.10	.10	.12	.15	.20
5	.10	.10	.10	.10	.15	.10
6	.10	.10	.15	.15	.20	.20
DIHEDRAL ANGLE 90° + TABULATED VALUE						
$R_1 - R_2$	1.81	2.07	1.30	2.00	2.00	2.05
$R_2 - R_3$	1.08	1.90	1.00	0.92	1.60	1.54
$R_3 - R_1$	1.42	1.80	1.16	1.24	1.57	1.83

ORIGINAL PAGE IS OF POOR QUALITY

Table 4-3

THERMAL/OPTICAL TEST CONDITIONS

CCR *	TEST DESCRIPTION		TEST NUMBER	POST VIBRATION	LASER FIELD ANGLES **
$\theta_A = 0^\circ$, θ_B 90°, $\theta_C = 0^\circ$	Isothermal - Ambient		1		8
$\theta_A = 0^\circ$, $\theta_B = 90^\circ$, $\theta_C = 80^\circ$	Isothermal - Ambient		15		8
			16		8
			24	X	15
	Isothermal - Vacuum		2		15
			17		15
			18		15
	Thermal Vacuum -30° C	No Sun - No IR	7		15
		No Sun - 1 Earth IR	9		8
		1 Sun - No IR	8		8
	Thermal Vacuum +30° C	No Sun - No IR	3		15
		No Sun - 1 Earth IR	6		8
		1 Sun - No IR	4		8

Table 4-3 (Continued)

THERMAL/OPTICAL TEST CONDITIONS

CCR ORIENTATION *	TEST DESCRIPTION	TEST NUMBER	POST VIBRATION	LASER FIELD ANGLES **
$\theta_A = 0^\circ$, $\theta_B = 90^\circ$, $\theta_C = 80^\circ$	Thermal Vacuum + 60° C	5		15
$\theta_D = 60^\circ$, $\theta_E = 40^\circ$, $\theta_F = 20^\circ$	Isothermal Ambient	10		8
		11		15
	Thermal Vacuum -30° C	19		15
	Thermal Vacuum $+30^\circ$ C	12		15
$\theta_D = 60^\circ$, $\theta_E = 100^\circ$, $\theta_F = 20^\circ$	Isothermal Ambient	20	X	15
		23	X	15
	Isothermal Vacuum	13	X	15
	Thermal Vacuum -30° C	21	X	15
	Thermal Vacuum $+30^\circ$ C	14	X	15
	Thermal Vacuum $+60^\circ$ C	22	X	15

* θ = Orientation of the cube with respect to polarization

8 = (A,D) $0^\circ \pm 15^\circ, \pm 30^\circ$, (B, E) 0°, 15°, (C,F) 0°

15 = (ABC) $0^\circ \pm 15^\circ \pm 30^\circ$, (DEF) $0^\circ \pm 15^\circ \pm 30^\circ$

** Incident Angles

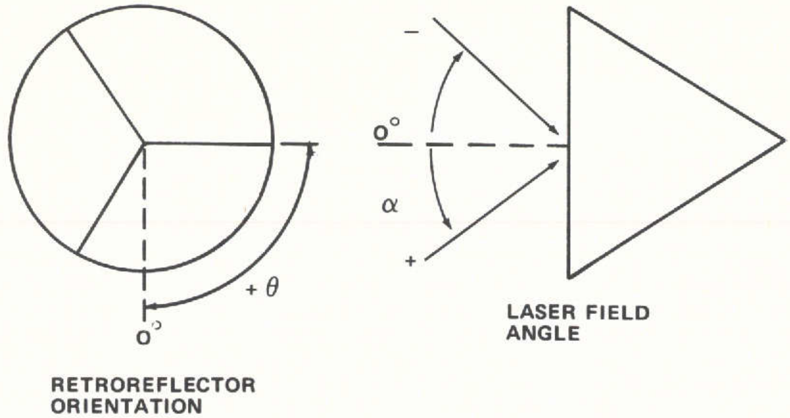


FIGURE 4–5. CCR INCIDENCE AND POLARIZATION ORIENTATIONS

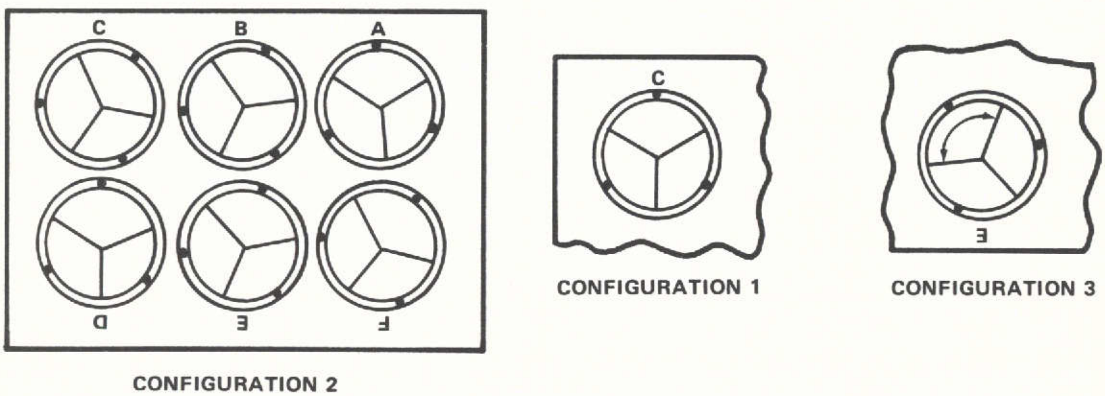


FIGURE 4–6. CCR TEST ARTICLE ASSEMBLY ORIENTATIONS

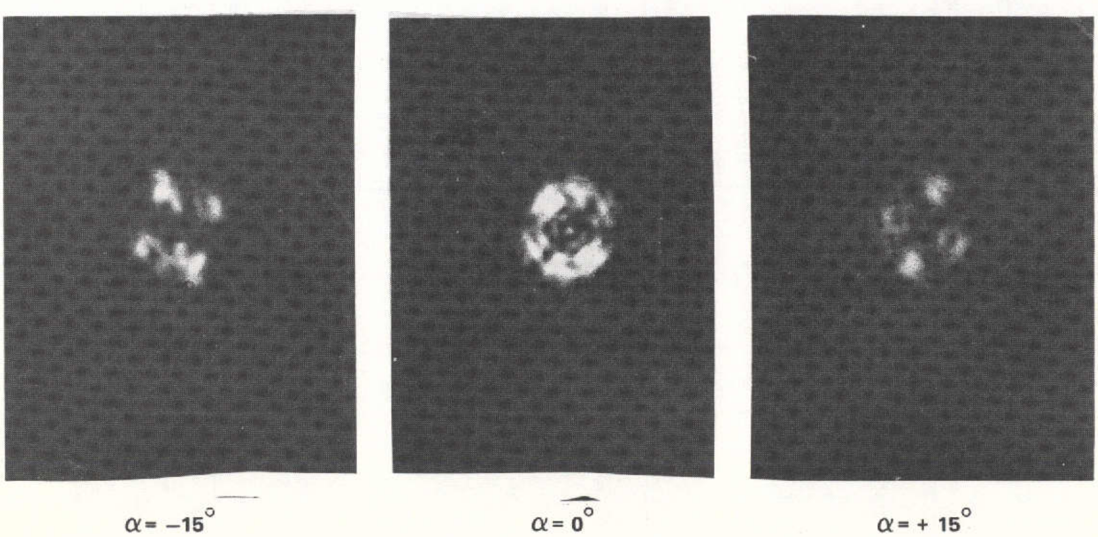


FIGURE 4–7. FAR FIELD DIFFRACTION PATTERNS

Figure 4-7 depicts some typical FFDP photographs taken during the test. They immediately show the distortion that takes place as the laser field angles are changed. Figures 4-8, 4-9, and 4-10 show the variation of power in the velocity aberration band as a function of angle of incidence. The energy varies drastically between angles as was expected, but it also varies appreciably from CCR to CCR. Figure 4-11 depicts the variation in the intensity as a function of test article temperature. This drawing shows that the CCR's do not have an intensity loss, due to thermal perturbations, greater than the 50% limit imposed by the LEVEL I NASA Headquarters specification (ES-LA-100).

4.5 CONCLUSIONS

The entire sequence performed both at MSFC and Bendix showed many facts:

a. The LAGEOS designs, as depicted in the test article, will meet the requirement for less than 50 percent optical performance degradation, when compared to isothermal performance, under the worst of environmental conditions.

b. Relatively large optical performance differences occurred between individual CCR's fabricated to the present specification.

c. Launch/boost vibrations do not adversely affect the optical performance.

d. The intensity in the inner physical 1/2 of the annulus (13.2 to 15.2 arc seconds) is approximately 1/2 that in the full annulus (13.2 to 16.9 arc seconds).

e. Variations as great as a factor of three (3) occur from one 60° segment of the annulus to the next.

f. The optical performance is not severely impacted by recess depth until the recess approaches a depth equal to approximately 1/4 of the CCR's clear aperture.

g. Intensity variations of approximately 20% occur as a result of a change in polarization angle (θ).

h. Intensity in the annulus, described by the velocity aberration angles, of the FFDP drops to its 1/2 power point at laser field angles (α) of approximately $\pm 15^\circ$.

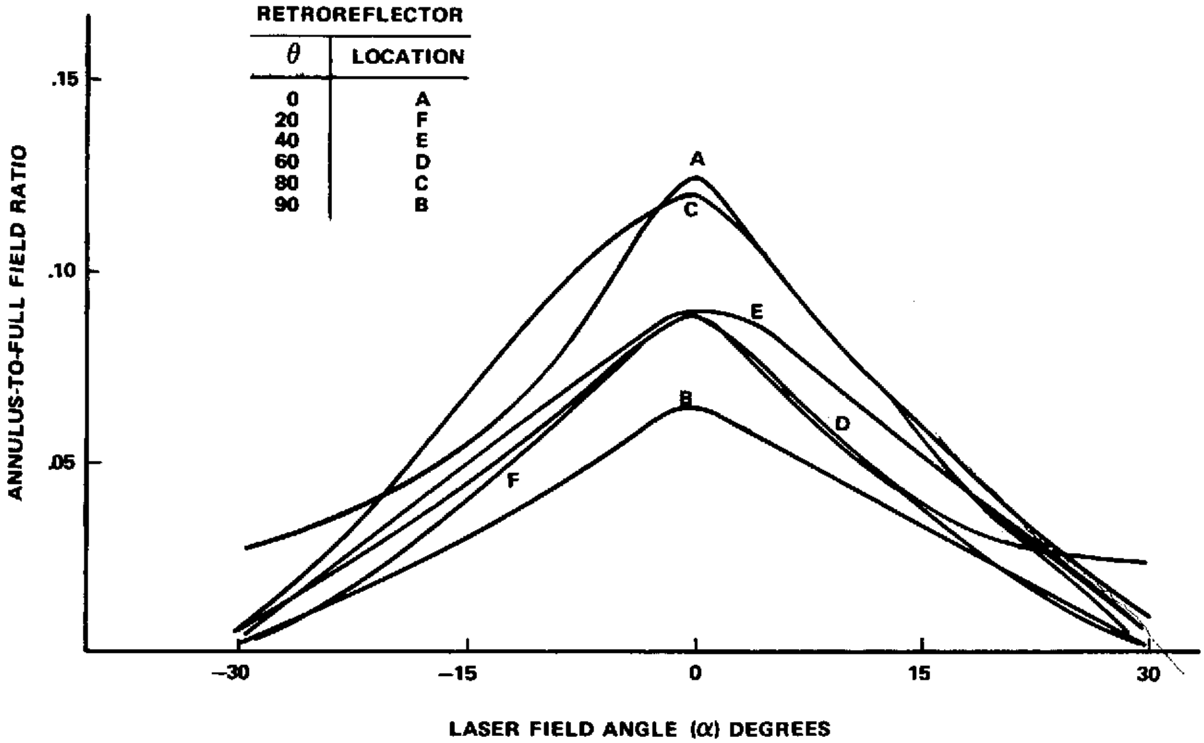


FIGURE 4–8. RETROREFLECTOR OPTICAL PERFORMANCE (ISO-THERMAL–VACUUM)

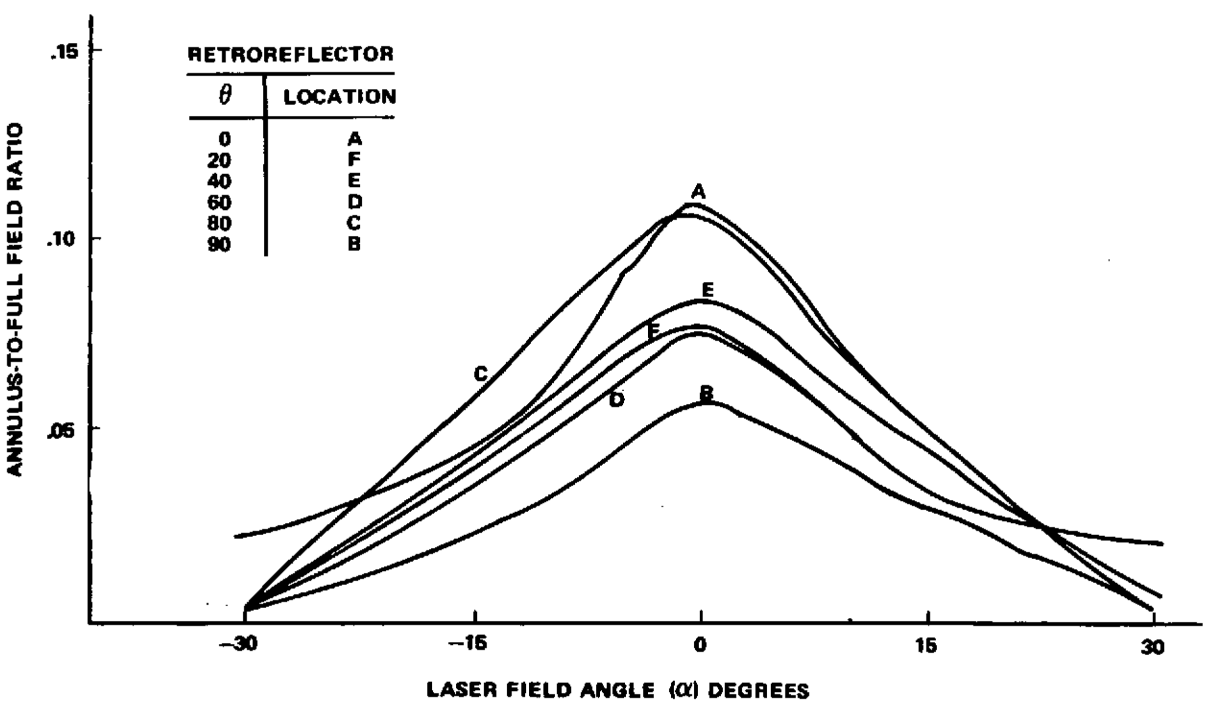


FIGURE 4–9. RETROREFLECTOR OPTICAL PERFORMANCE (−30° C – VACUUM)

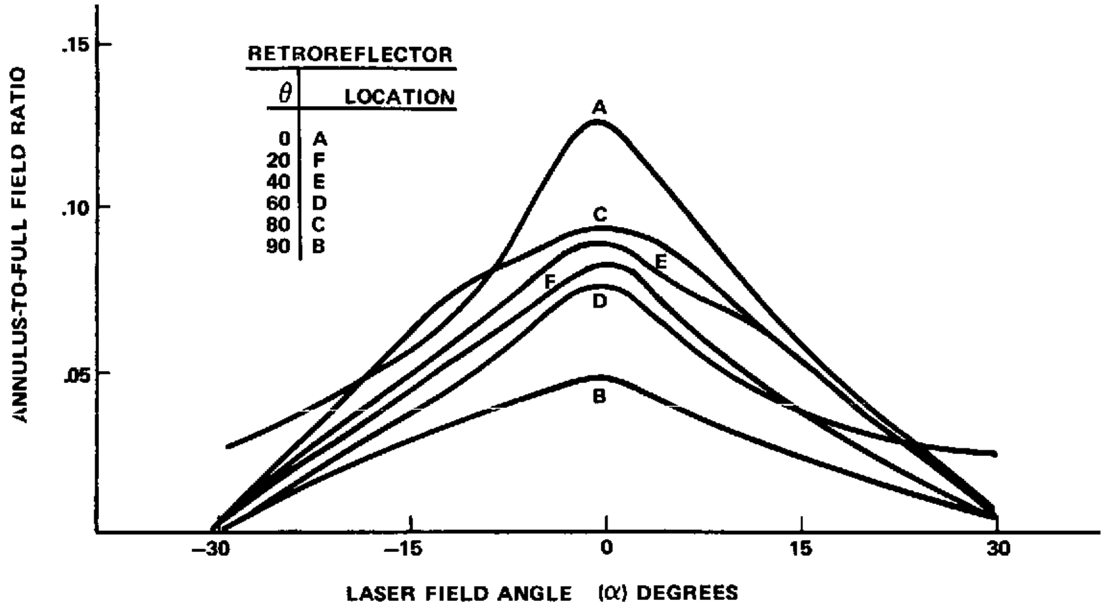


FIGURE 4–10. RETROREFLECTOR OPTICAL PERFORMANCE (+30° C – VACUUM)

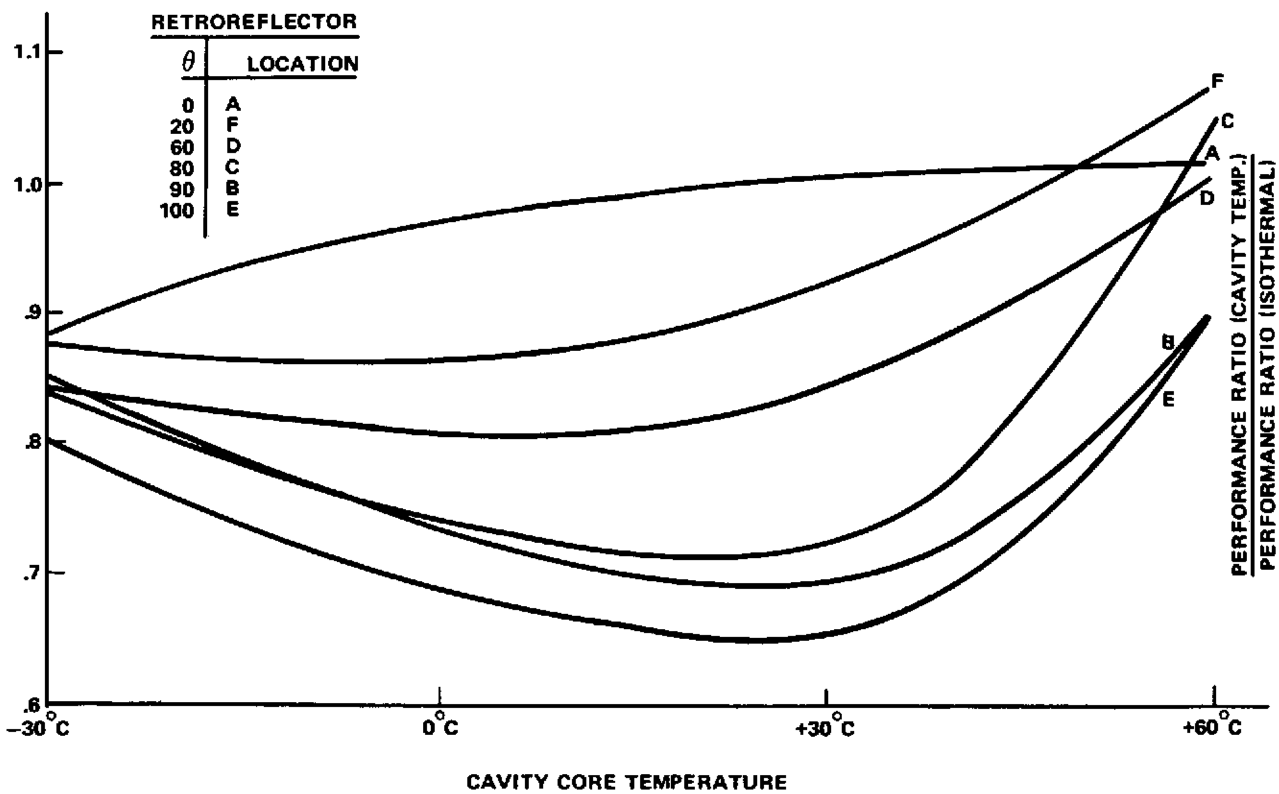


FIGURE 4–11. RELATIVE EFFECT OF T-V CONDITIONS ON OPTICAL PERFORMANCE LASER FIELD ANGLE ($\alpha = 0°$)

5.0 Dynamic Considerations

5.1 Vibration, Acoustics, and Shock

5.1.1 Criteria, Analysis, and Test

The spacecraft qualification criteria used for this study were obtained from Goddard Space Flight Center (GSFC) documentation on the Delta launch vehicle augmented by discussions with GSFC dynamics personnel. These criteria are included in the LAGEOS interface control document, 13M13578.

Early vibration tests were performed at MSFC to determine the feasibility of using a modified GEOS-C retroreflector mounting configuration for the LAGEOS. Test results indicated that the modified GEOS-C configuration is acceptable but would require further stiffening of the clip. This fact was a consideration, although not a major influence, in the selection of the modified ALSEP retroreflector mounting to be used on the LAGEOS spacecraft.

Analysis and testing were primarily accomplished by Bendix Aerospace Systems Division under contract NAS8-30658. A six-retroreflector coupon was tested to random vibration, sine, and equivalent shock spacecraft qualification levels. No acoustic tests were performed as the effect of acoustics on the LAGEOS spacecraft was determined to be negligible. A report on the analyses/tests performed by Bendix can be found in the Bendix Phase B report BSR 4159.

5.1.2 Results and Recommendations

The LAGEOS test specimen endured the dynamic environment with no damage to components, no optical degradation of the retroreflectors, and no significant loosening of the retaining mechanism. Therefore, it is not considered necessary for the LAGEOS flight assembly to undergo dynamic qualification or acceptance testing after installation of the retroreflectors. It would be highly desirable, however, for the LAGEOS spacecraft, or a suitable mass simulation, to be included in the launch vehicle adapter dynamic and separation testing, which will be accomplished by MDAC.

5.2 Dynamic Balance and Mass Characteristics

Three design requirements are critical to the mass characteristics and dynamic balance of the LAGEOS. These requirements are: (a) the ratio of the moment of inertia with respect to the Y and Z axes must be equal to or greater than 1.03, (b) the center of mass must coincide with the center of geometry within 1 millimeter, and (c) the angle between the X axis and the principle axis of inertia (α) cannot exceed 0.02 radians. The requirement most sensitive to mass distribution from nominal is the principle axis orientation requirement. This is because of the moment of inertia with respect to each of the axes is nearly equal.

5.2.1 Predicted Mass Characteristics

The nominal mass characteristics for both the flight LAGEOS and the balance test model were calculated. The test model is identical to the flight model except for the retroreflector installations. The reflector holes were not drilled in the test model. That is the reason it is heavier than the flight LAGEOS. The predicted mass characteristics are presented below.

		Test Model	Flight Model
Mass	M	440.3 Kg	409.8 Kg
Moment of Inertia	IXX	13.137 Kg-M^2	11.516 Kg-M^2
Moment of Inertia	IYY	12.712 Kg-M^2	11.084 Kg-M^2
Moment of Inertia	IZZ	12.712 Kg-M^2	11.084 Kg-M^2
Product of Inertia	IXY	0.0	0.0
Product of Inertia	IXZ	0.0	0.0
Product of Inertia	IYZ	0.0	0.0
C.G. Offset	XCG	0.0	0.0
C.G. Offset	YCG	0.0	0.0
C.G. Offset	ZCG	0.0	0.0

The ratios of the moment of inertias were 1.033 and 1.039 for the test model and flight model, respectively.

5.2.2 Balance Model Test Program

A test program was conducted to determine the mass characteristics of the LAGEOS test model. The primary objective of this program was to verify that the test model meets the three critical design requirements discussed previously. Also, a test was performed to show the sensitivity of the center of mass to center of geometry relationship (c.g. offset) by adding weights to the model.

The weight of the model was measured and the moment of inertia with respect to each of the axes was determined by using a spin balance table fitted with a torsion bar. A comparison of the measured values to the predicted values is shown below.

	Measured	Predicted
M	440.0 Kg	440.3 Kg
IXX	13.11 Kg-M^2	13.14 Kg-M^2
IYY	12.69 Kg-M^2	12.71 Kg-M^2
IZZ	12.71 Kg-M^2	12.71 Kg-M^2

As can be seen, the comparison between the predicted and measured values was excellent. The ratio of IXX to IYY and IZZ was 1.033 and

1.031, respectively. These values are within the ratio of inertia specification discussed previously.

The center of mass offset and products of inertia were determined by using a spin balance machine. The readout of the machine consisted of the locations and amount of weight required to balance the test article about the spin axis. This information was used to compute the center of mass offset from the spin axis and the products of inertia with respect to spin axis.

Tests were performed using each of the three axes of the model as the spin axis. The results of these tests are shown below.

Spin Axis	XCG MM	YCG MM	ZCG MM	IXY $Kg\text{-}M^2$	IXZ $Kg\text{-}M^2$	IYZ $Kg\text{-}M^2$
X	____	-.015	.071	-.005	-.001	____
Y	-.003	____	-.119	-.004	____	-.010
X	.033	-.091	____	____	.003	-.007

It was apparent from these data that there were significant differences in the results depending on the spin axis. A study of the perimeter mapping data taken during the alignment of the model on the balance table indicated the geometric axis of the model did not coincide with the spin table axis. This accounted for most of the differences in the center of mass offset data. Also, a study of the test fixture balance data indicated a small dynamic unbalance that was affecting the product of inertia data. These corrections were made to the data and the results are shown below.

Spin Axis	XCG MM	YCG MM	ZCG MM	IXY $Kg-M^2$	IXZ $Kg-M^2$	IYZ $Kg-M^2$
X	_____	-.006	.025	.000	-.001	_____
Y	-.003	_____	.008	-.004	_____	-.006
Z	-.043	.023	_____	_____	-.001	-.007

Based on these data, the distance from the center of geometry to the center of mass is in the range of .010 to .055 millimeters. The angle between the flight axis (X axis) and the principle axis of inertia was computed from these data to be from .002 to 0.010 radians.

It should be noted that the alignment mapping data indicate a variation in the radius of the model of .002, .189, and .157 millimeters for rotations around the X, Y, and Z axes, respectively. Based on these data, it would appear that the LAGEOS performance would be affected more by variations in the radius of the satellite than by the center of geometry to center of mass offset.

The last spin test performed was a test spinning about the X axis (flight axis) with weights attached to the surface of the test model. Three attached weight conditions were tested. The weights were located 22.98° above the Z axis in the X-Y plane. The table shown below contains the results of this test compared with the predicted values for the C.G. offset in the X-Z plane.

Attached Weight Kg	Measured C.G. Offset MM	Predicted C.G. Offset MM
0.388	0.27	0.25
1.060	0.72	0.69
1.851	1.28	1.24

The predicted values compare favorably with the measured values. The difference is attributed to the C.G. offset of the test model which was not included in the predicted values and the accuracy with which the measured data could be corrected for misalignment.
It can be concluded that the LAGEOS balance test model is within the design specifications critical for balance by a safe margin.

5.2.3 Results and Recommendations

The results of the LAGEOS balance model test program show that all mass property characteristics are near the predicted nominal values and well within the performance and design specifications. Therefore, it is appropriate to consider omitting the flight LAGEOS balance test program. The only difference between the balance model that was tested and the flight model is the retroreflectors. A study was performed to determine the effect of the retro-reflector installation using worst-case tolerances. It was determined that the center of geometry to the center of mass could be shifted a maximum of 0.79 millimeters. Therefore, it can be concluded that the 1-millimeter center of geometry to center of mass limit cannot be exceeded if manufacturing tolerances are within specification. A study was also performed using worst-case tolerances on the retroreflector installation to determine the maximum possible product of inertia with respect to the X axis (flight axis). The maximum product of inertia was determined to be 0.04 Kg-M^2, which can cause a principle axis inertia shift of 0.09 radians. The maximum flight axis to principle axis angle specified by the LAGEOS ICD is 0.02 radians. Therefore, it is possible that the 0.02-radian requirement will not be met after the retroreflectors are installed. The principle axis angle requirement is imposed on the LAGEOS by the Delta launch vehicle restraints and is specified in the Delta spacecraft design restraints document. Deviations from this requirement are possible if coordinated with the Delta project.

Based on the above discussion, it is evident that a balance test of the flight LAGEOS can be omitted from the program if the following actions are taken: (a) the maximum angle between the flight axis and principle axis of inertia of 0.02 radians is relaxed to 0.1 radians and (b) the manufacturing tolerances are verified to be within specification.

6.0 MANUFACTURING

6.1 General

To our knowledge no one has ever machined a solid sphere of this size before, therefore, we had no proven procedure to follow. However, the fabrication of the balance model of the LAGEOS Satellite turned out to be fairly basic and simple. In our opinion this was due to the evolved design of the weight, Part Number 30M20456. If the design had followed the core segment concepts depicted in Figure 2-3, Page 2-5, it would have been considerably more difficult to machine and even more difficult to assemble.

The balance model was machined and assembled without the benefit of tooling; however, several shop aids were devised and utilized.

The only raw material purchased was a forged billet of 6061 aluminum alloy 24 inches in diameter and 36 inches long. This forged billet was obtained from Union Carbide Corporation, Nuclear Division, United States Atomic Energy Commission, Oak Ridge, Tennessee. The other raw materials used in the fabrication of the LAGEOS Balance Model and the shop aids were available and residual to earlier MSFC programs. The ALCOA aluminum billet was received in the O condition and was treated to the T-6 condition.

6.1.1 Sphere Machining Operations

The first machining operation was to set up and saw the billet into three (3) equal disks twelve inches thick. The two end disks were used for making the two sphere halves. The disks were faced off and the 12.5 by 4.7 inch recess was rough bored. At this point, the disks were stress relieved. The disks were rough rounded into half spheres on a large Monarch lathe using a Monarch Electro-Gage Tracer. The sphere halves could have been completely finished on this lathe; however, the final smoothing finish would have had to be performed by hand which could have introduced a human error. So it was deemed necessary to put the final contour on by using a fly cutter mounted on a turntable on a Pratt & Whitney jig bore machine. The contour and final surface finish was obtained by use of the fly cutter and no lapping operation was required.

6.2 Retroreflector Indexing

The drilling of the retroreflector location marks were also performed on this indexing turntable mounted on the Pratt & Whitney jig bore machine.

6.2.1 Brass Core Weight Machining

When the brass billet was cut to size, it was discovered to have a flaw or cold shut in the very center of the billet and extending throughout the length of the billet. Since no other raw material was available to use in making the weight and since the schedule would not permit the time required to purchase a new billet, a fix was designed. The center of the billet was bored out and a beryllium copper shaft was rough machined, hardened and finish machined. The finish machining left the copper shaft 0.0018 inch over size to obtain a shrink fit. The brass weight was heated with torches while it was slowly turned in a lathe and the beryllium copper shaft was submerged in LN_2. The cold shaft was then inserted by hand into the hot weight to obtain a homogeneous structure.

6.3 Assembly

The brass weight is guided into the bottom sphere half using a lifting and centering shop aid and the top sphere half is then lowered onto the brass weight and the nuts are torqued to 100 foot pounds. The balance model was weighed using a Load Cell and Digital Force Computer.

7.0 Operations and Ground Support Equipment Concepts

7.1 Purpose

This section provides guidelines for the design, development, and manufacture of the LAGEOS handling and transportation equipment. Also included is a preliminary description of the proposed support equipment concepts. It is the intent of the design concepts to familiarize the reader with the basic classifications and operational areas of LAGEOS support equipment use. The concepts are not intended to establish design objectives.

7.2 Scope

The objective is to provide all the support equipment necessary to support the LAGEOS activities, at minimum cost, and to be compatible with the projected activity requirements.

7.3 Groundrules and Assumptions

The following groundrules and assumptions form the criteria governing the development of the LAGEOS operations functional flow diagram. The flow covers the fabrication aspects of the satellite from the receipt of the raw material billets to the final stacking operation necessary to prepare to launch vehicle 2913. The same criteria influenced the equipment concepts that are portrayed:

a. Minimum cost.

b. Make maximum use of existing NASA GFE.

c. Incorporate commonality into the support equipment to reduce new/unique requirements throughout the flow of the LAGEOS.

d. Assume special transportation and handling required.

e. All satellite supports, restraints, and handling functions will make use of the existing threaded attachments.

f. Final surface finish performed prior to boring CCR mount holes.

g. No final spin/balance test to be performed prior to shipment to WTR after boring CCR mount holes.

h. LAGEOS final surface cleanliness and verification performed before shipment to WTR.

i. Shipping container removable encapsulation bag will satisfy requirement to maintain satellite surface cleanliness.

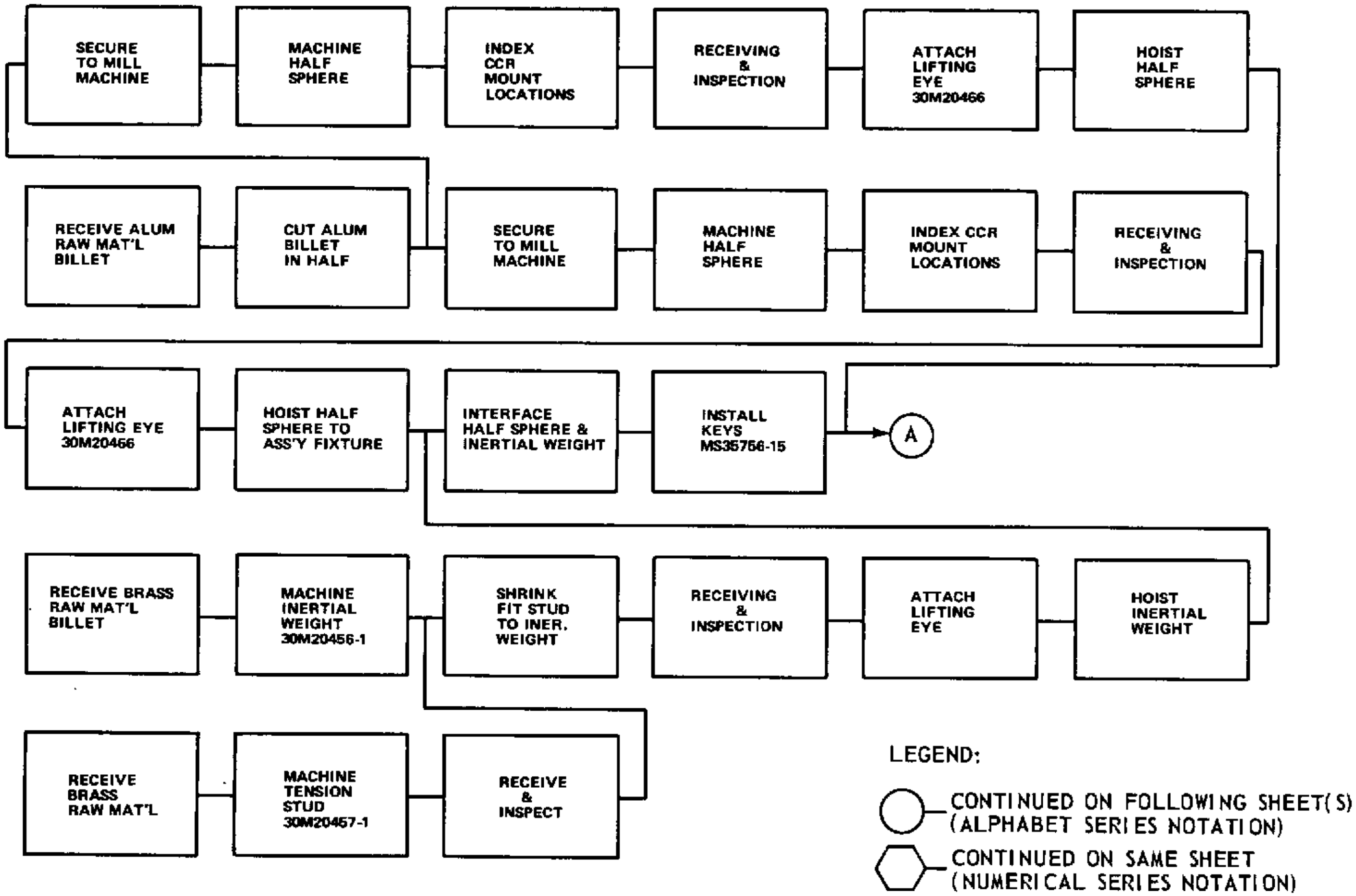
j. Fit checks with LAGEOS satellite and flight separation assembly and cradle, performed in Building 836, Spacecraft Laboratory No. 2, WTR.

k. Modify existing Saturn S-IC stage propellant valve checkout and handling stand to satisfy LAGEOS CCR installation requirements.

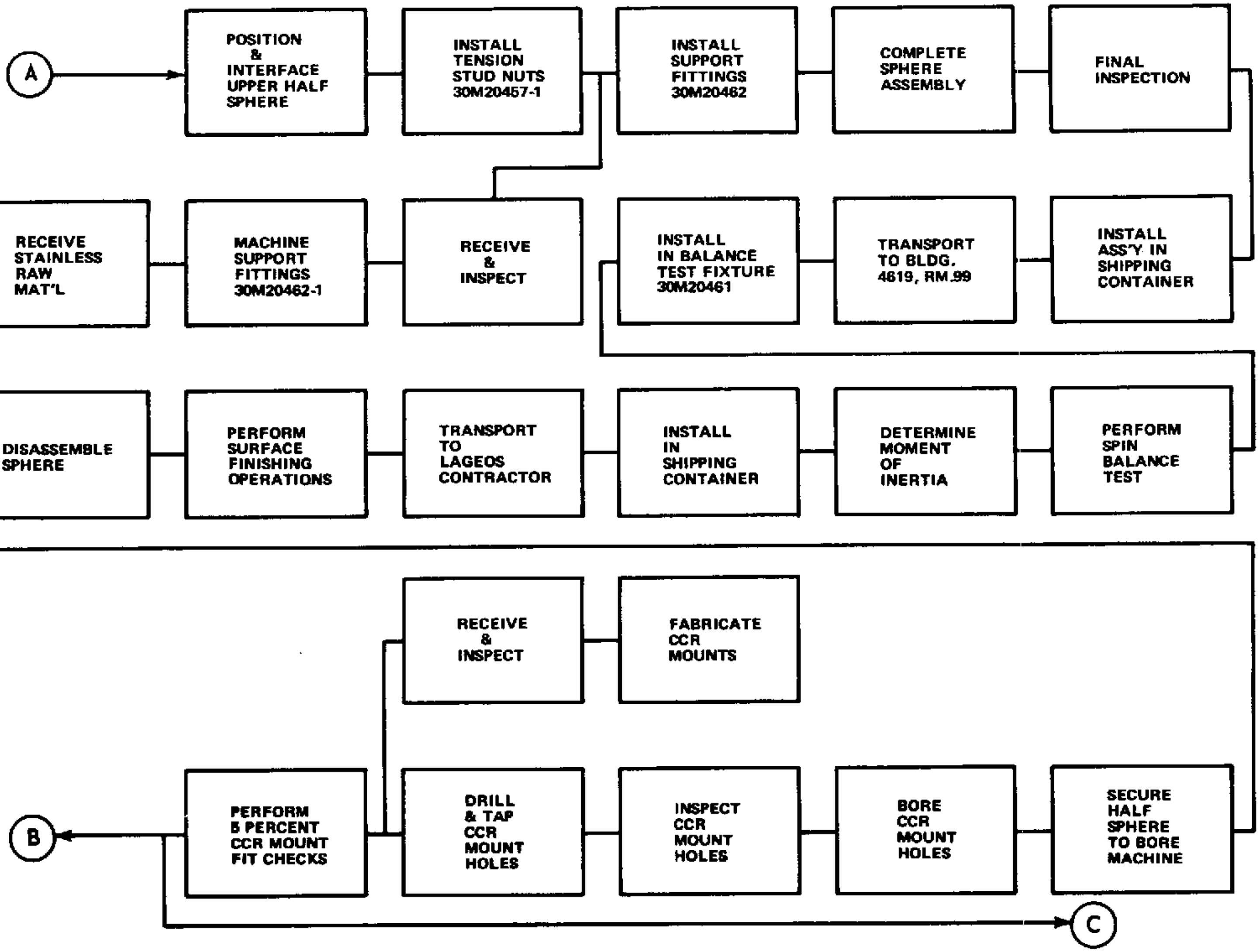
l. CCR's installed at the WTR Spacecraft Laboratory No. 2 cleanroom.

ORIGINAL PAGE IS OF POOR QUALITY

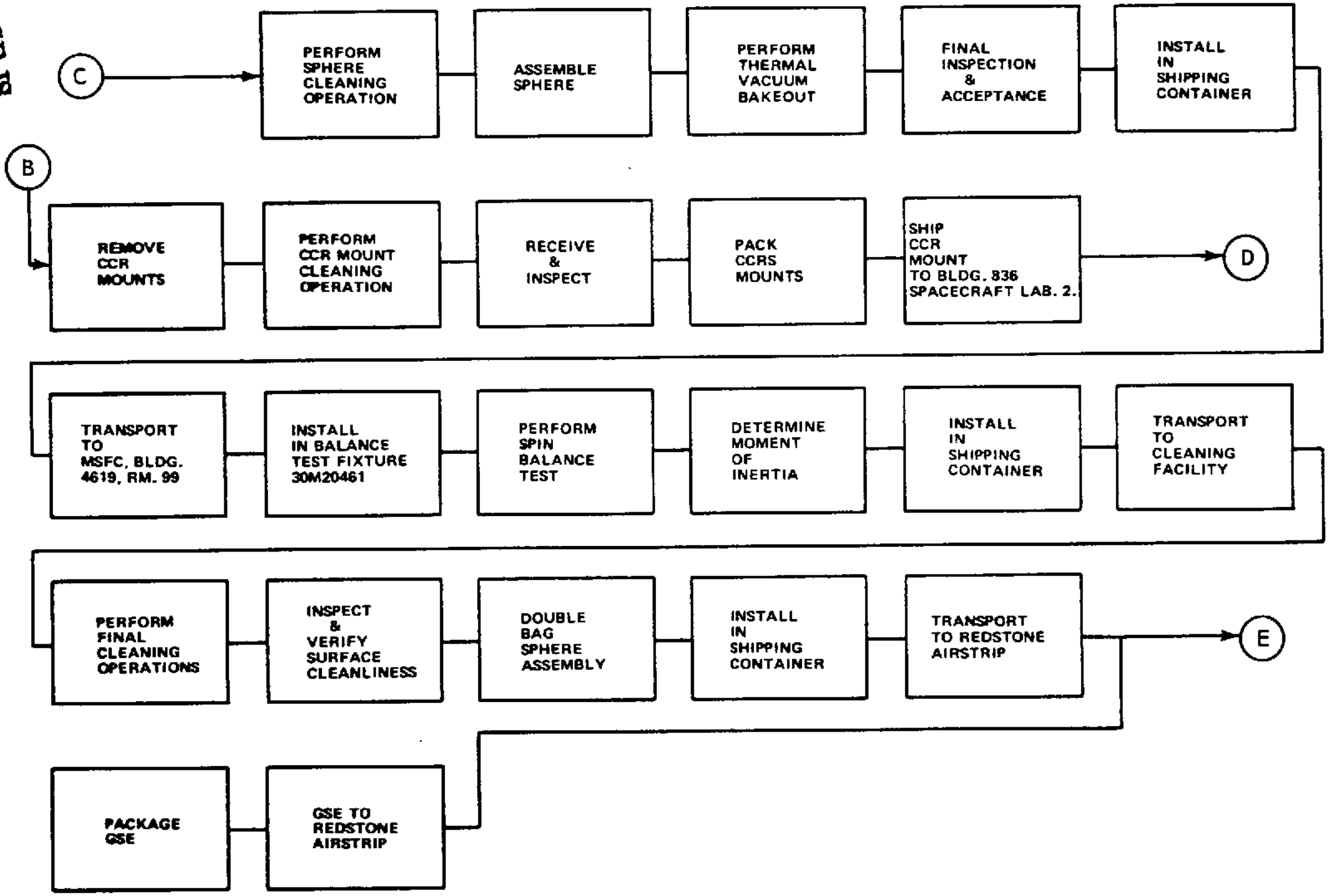
LAGEOS OPERATIONS FUNCTIONAL FLOW SEQUENCE DIAGRAM



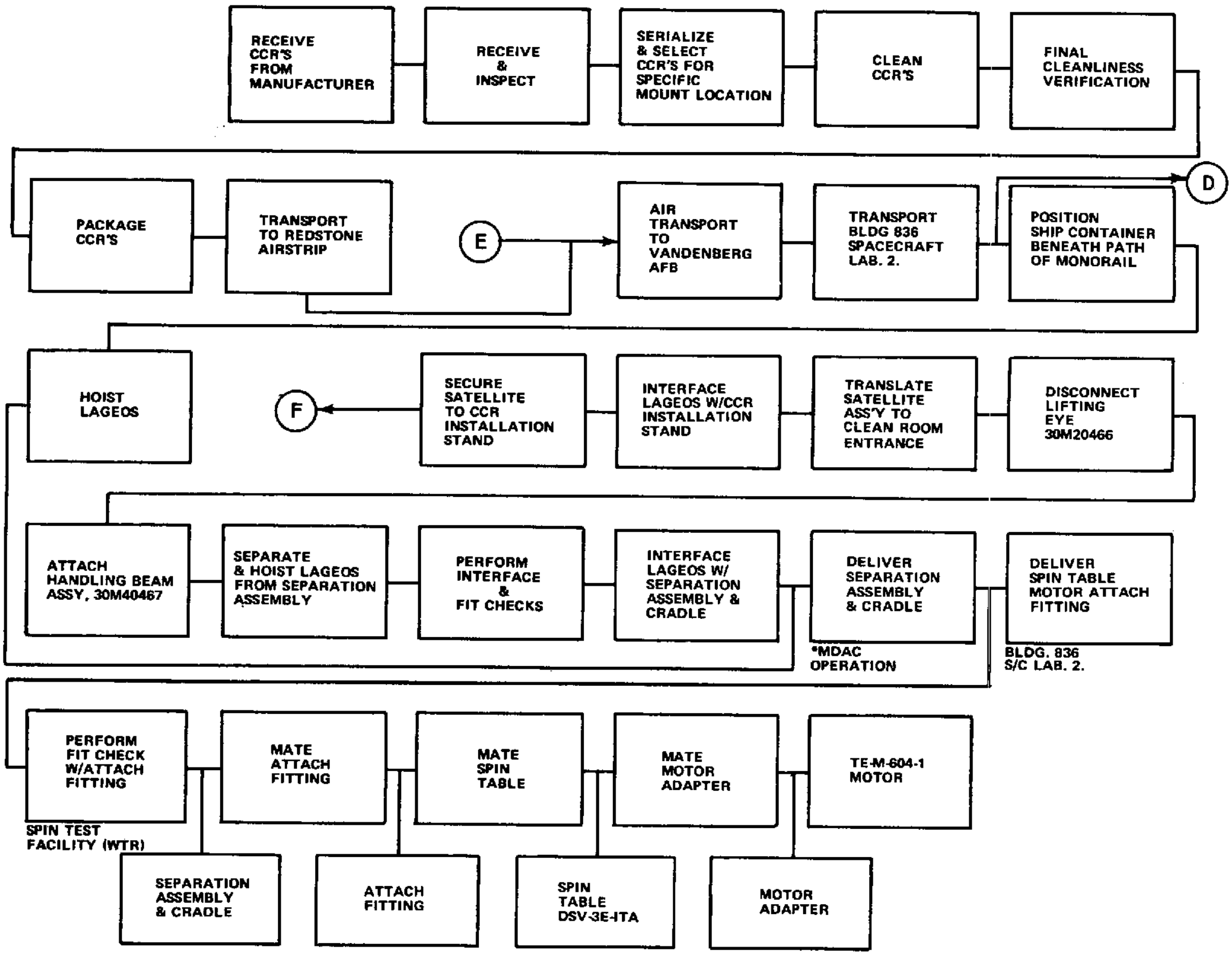
LAGEOS OPERATIONS FUNCTIONAL FLOW SEQUENCE DIAGRAM



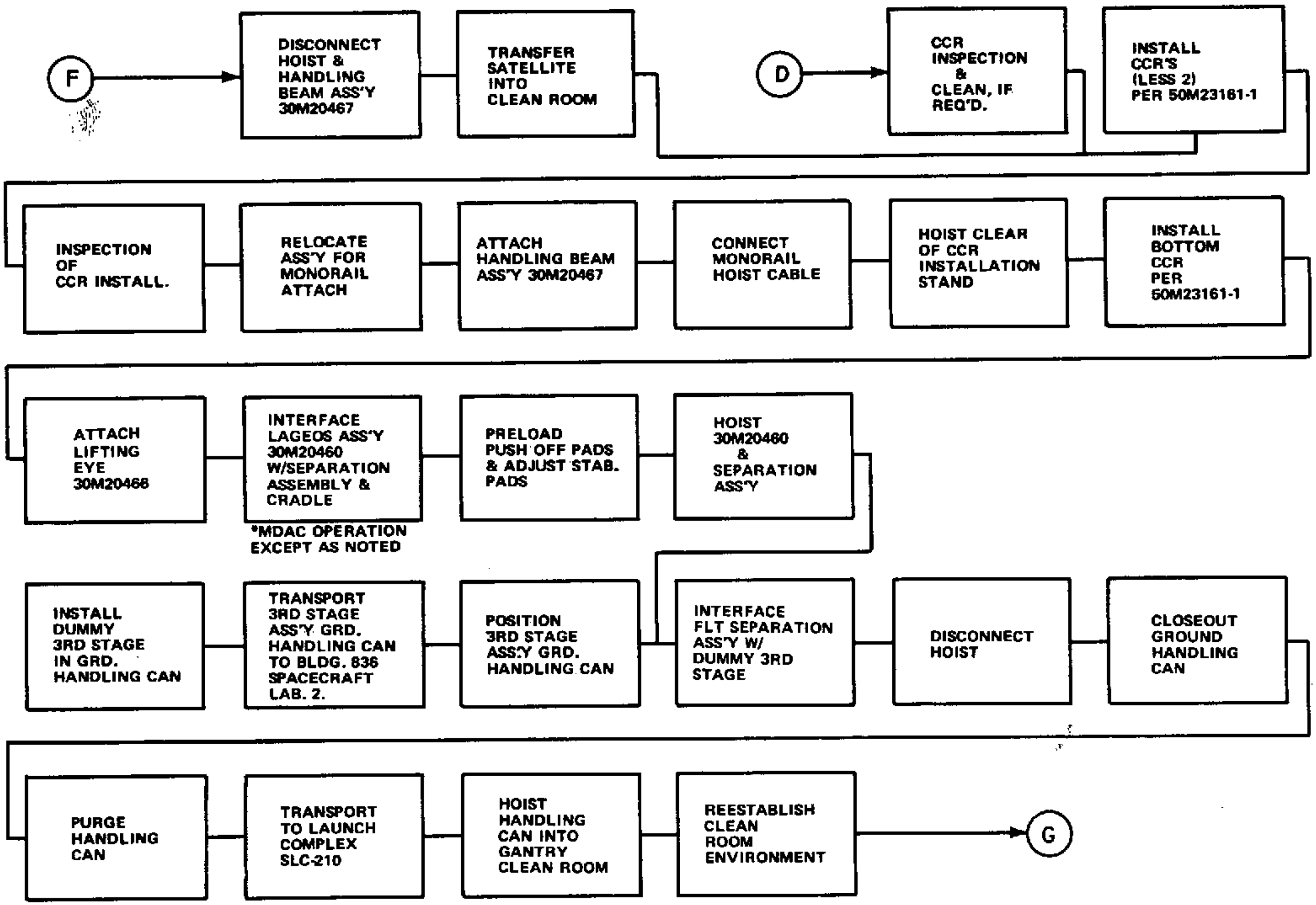
LAGEOS OPERATION FUNCTION FLOW SEQUENCE DIAGRAM



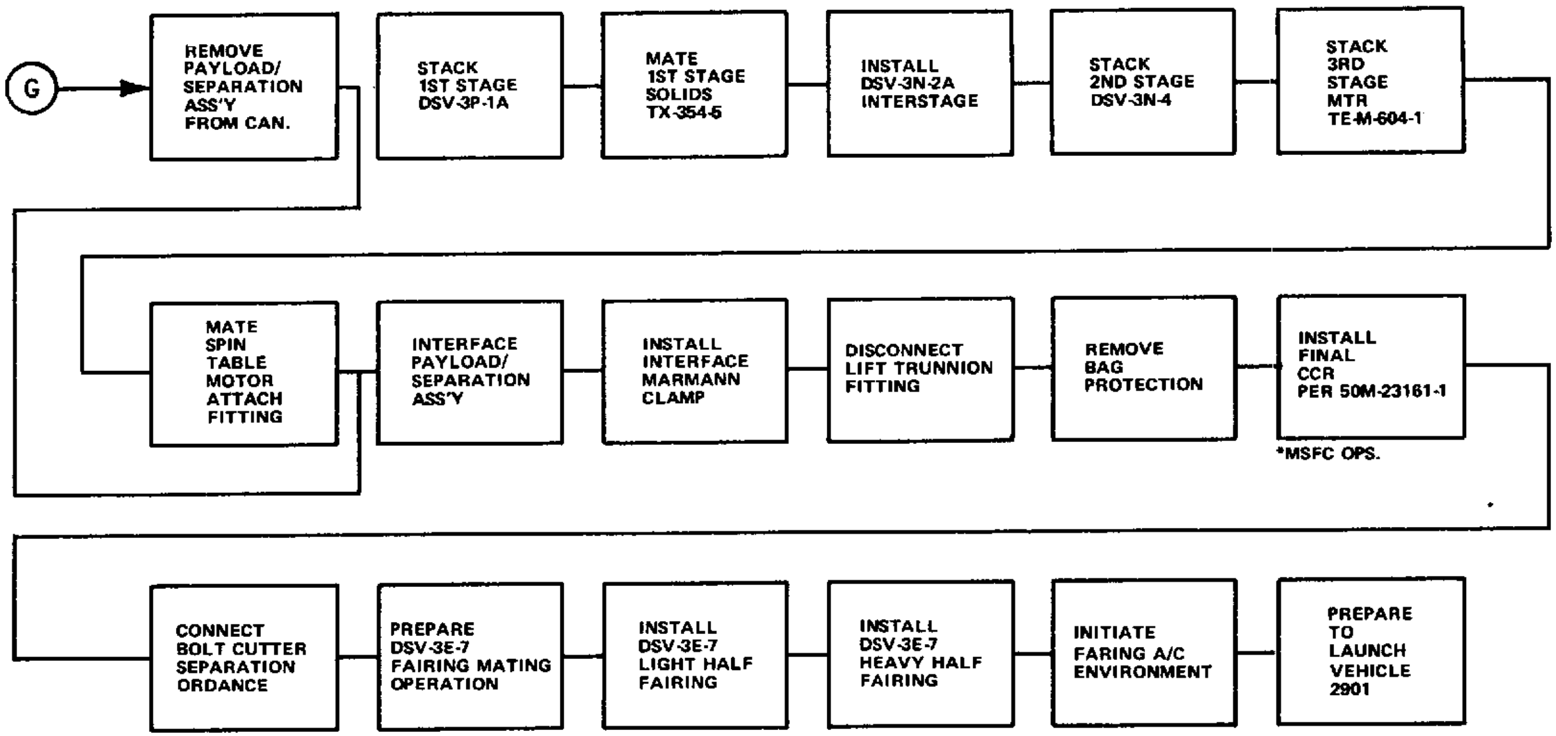
LAGEOS OPERATIONS FUNCTIONAL FLOW SEQUENCE DIAGRAM



LAGEOS OPERATIONS FUNCTIONAL FLOW SEQUENCE DIAGRAM



LAGEOS OPERATION FUNCTION FLOW SEQUENCE DIAGRAM



APPENDIX A

SUPPORT EQUIPMENT CONCEPTS

NOMENCLATURE:

LAGEOS Inertial Weight
Handling Fixture

DESIGN SOURCE:

Manufacturing

PURPOSE:

To allow the machined inertial weight to be handled and hoisted into place for the interfacing operations of the half sphere with the inertial weight and satellite buildup.

SUPPORTING ACTIVITY:

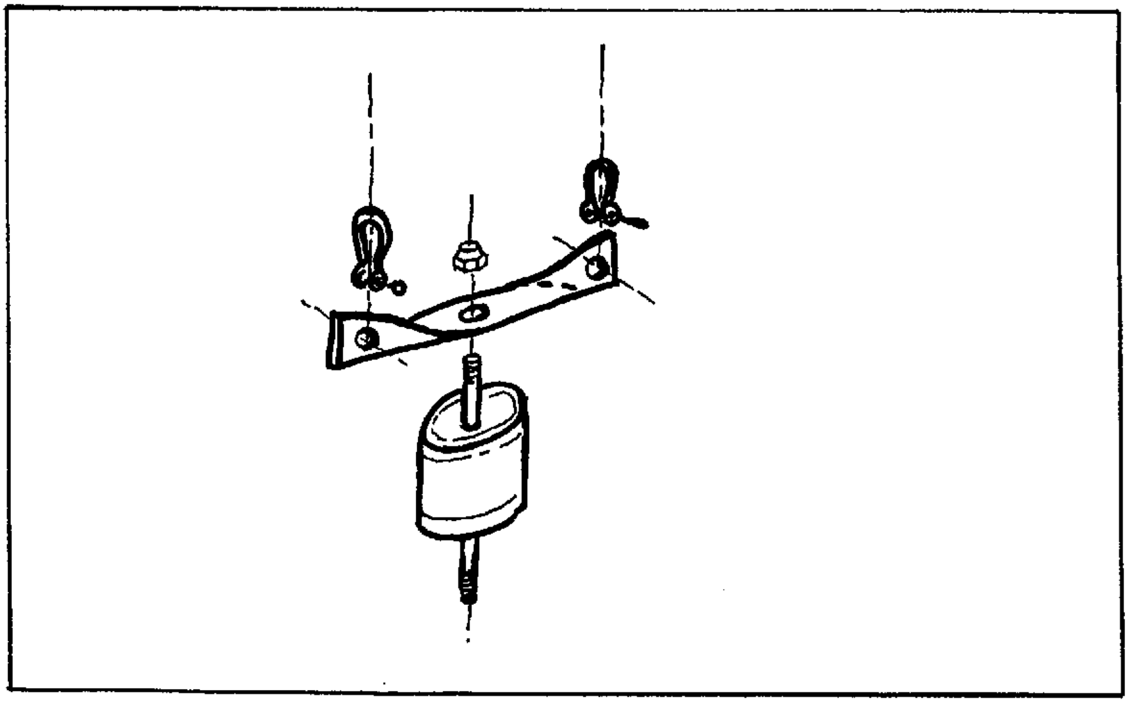
Manufacturing, CCR Mount
Installation

TECHNICAL REFERENCE:

Derived

FUNCTIONAL DESCRIPTION:

Consists of a metal handling fixture with a center located hole to accept one end of the inertial weight tension rod. A stud nut completes the capture. The outer extremities of the handling fixture are drilled to accept a screw pin shackle. A cable arrangement connected to a hoisting device lifts the assembly for handling.



NOMENCLATURE:

Satellite Assembly Fixture

DESIGN SOURCE:

In-House

PURPOSE:

To support half spheres during manufacturing and satellite assembly.

SUPPORTING ACTIVITY:

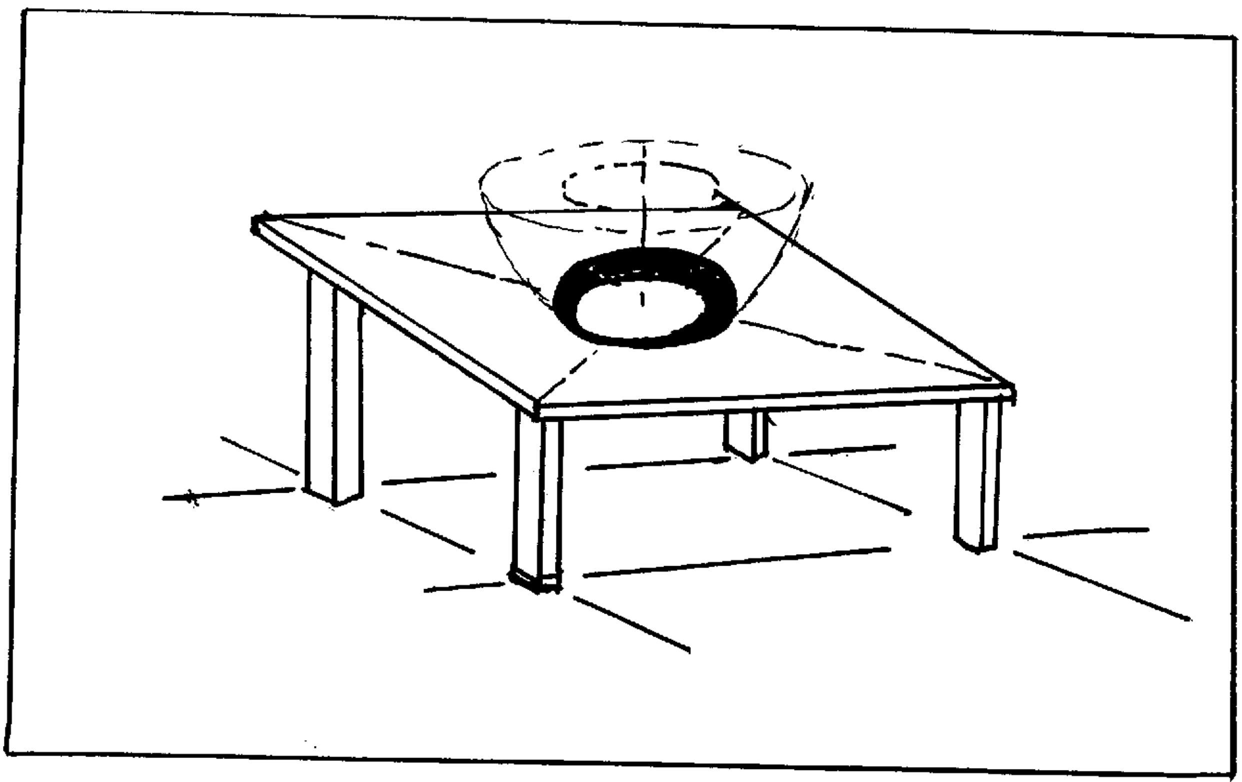
Manufacturing Facility

TECHNICAL REFERENCE:

Derived

FUNCTIONAL DESCRIPTION:

Latitude hole lined with felt bearing material to allow for support and position of the half sphere necessary in the assembly buildup of the inertial weight and satellite assembly.



NOMENCLATURE:

Lifting Eye
30M20466

DESIGN SOURCE:

In-House

PURPOSE:

To allow for the satellite hoisting and lifting operations during manufacturing and dynamic spin testing.

SUPPORTING ACTIVITY:

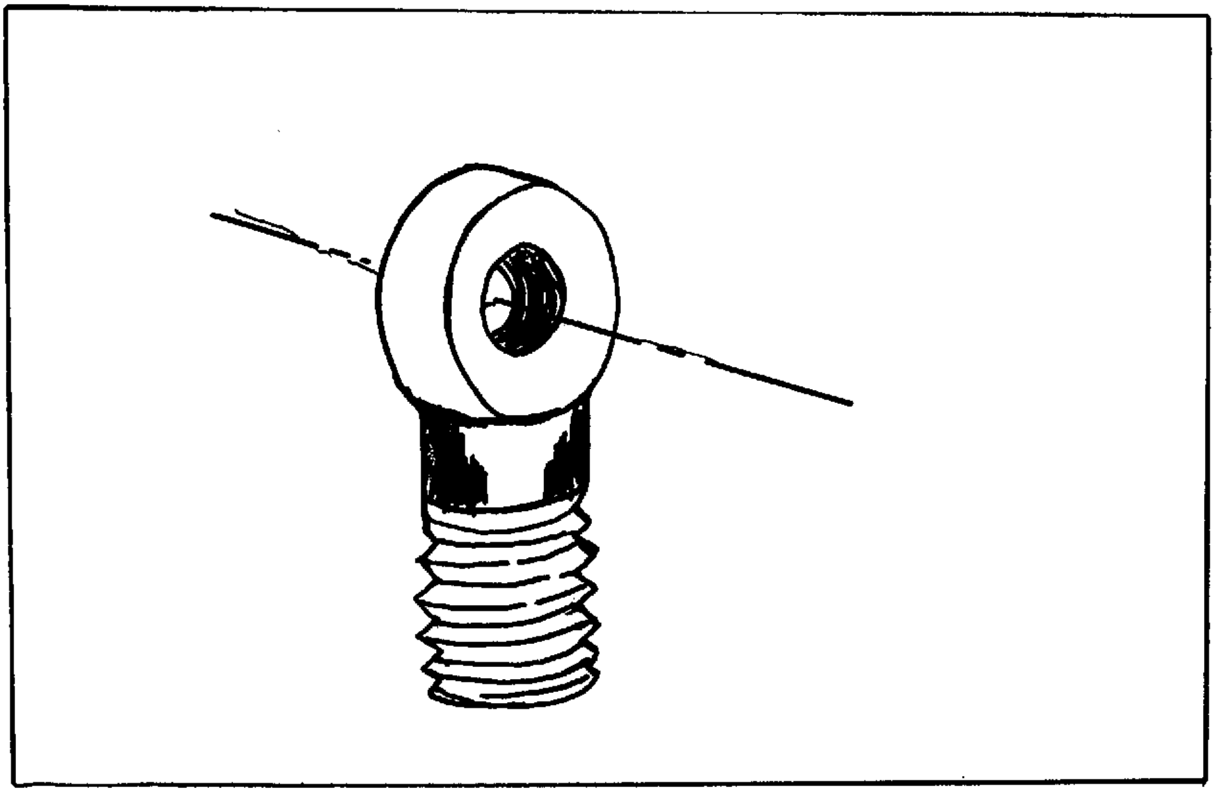
Manufacturing, Spin Balance Facility

TECHNICAL REFERENCE:

Derived

FUNCTIONAL DESCRIPTION:

A machined fitting with 1.500-12UNF-2B male threads that interface with the hemispheres and/or satellite assembly.



NOMENCLATURE:

Balance Test Fixture
30M20461

DESIGN SOURCE:

In-House

PURPOSE:

Interface with the dynamic balance/spin fixture and supports and restrains the satellite assembly required for dynamic spin balancing.

SUPPORTING ACTIVITY:

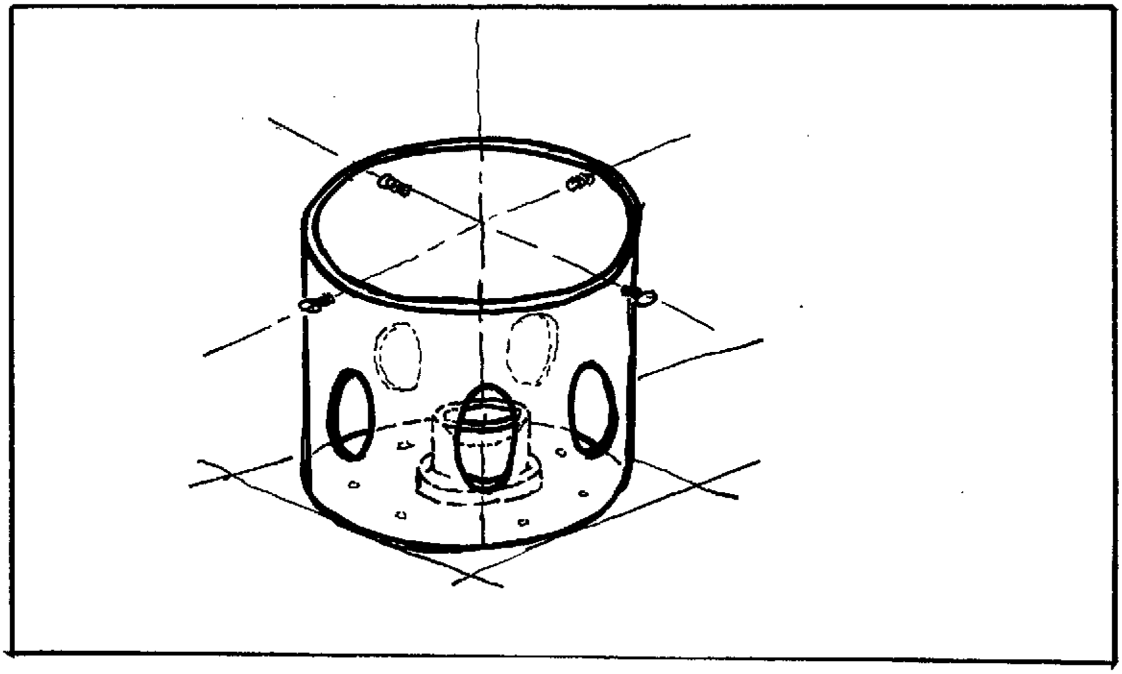
Dynamic Spin Balance Facility

TECHNICAL REFERENCE:

Derived

FUNCTIONAL DESCRIPTION:

A machined aluminum cylinder with base plate and hand access holes surrounding the exterior of the cylindrical fixture. At the center of the fixture and attached to the base plate is a machined satellite support. Four adjustable fingers, located 90° apart, and forward on the fixture provide for the lateral restraint of the satellite assembly during the spin balance operations. The base plate has the appropriate holes required to interface the fixture to the spin table. The test fixture is balanced separately from the satellite to minimize the fixture's influence with that of the satellite.



NOMENCLATURE:

LAGEOS Shipping Container

DESIGN SOURCE:

In-House

PURPOSE:

To restrain and environmentally protect the LAGEOS satellite during shipping and storage of the satellite assembly.

SUPPORTING ACTIVITY:

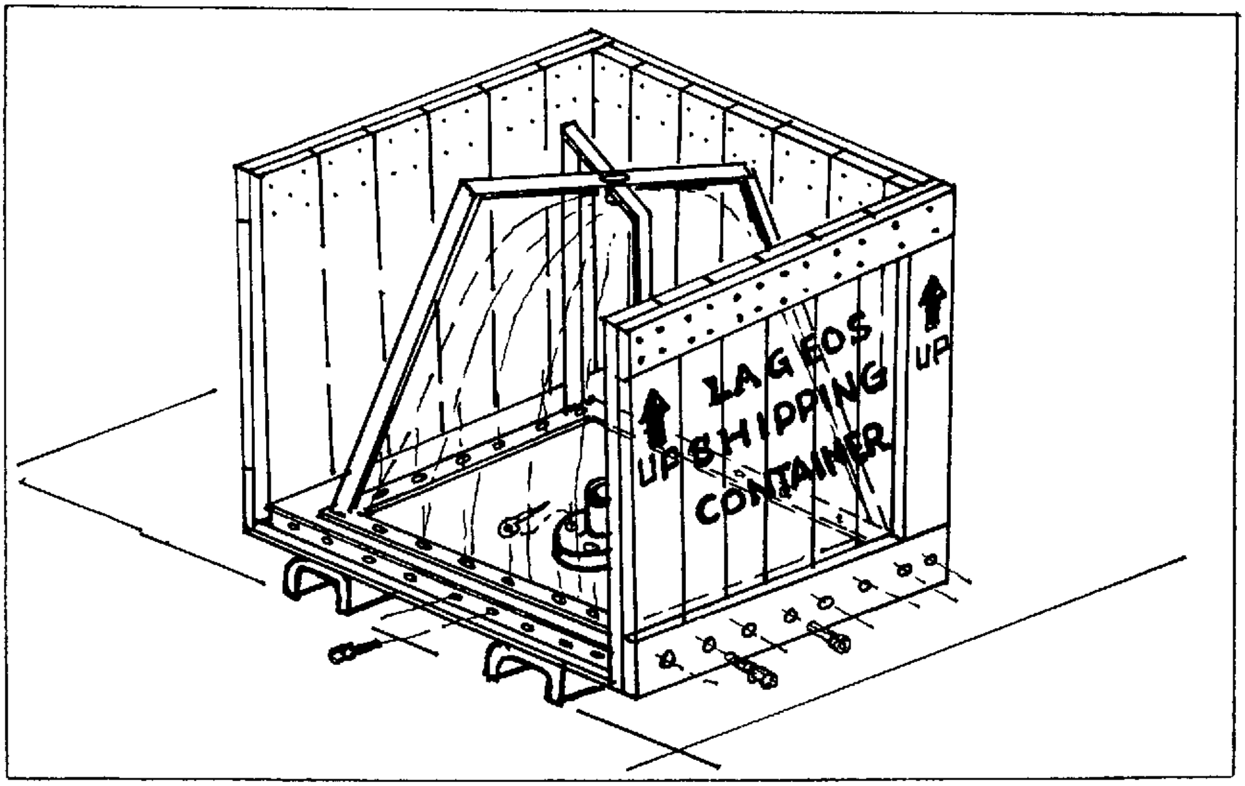
Manufacturing, qualification (static & dynamic balance) test, acceptance test (physical, thermal & spin balance); CCR installation fit, building 836, So. Vandenberg

TECHNICAL REFERENCE:

ES-LA-100 Basic Spec.
Para 3.1.1.2
ICD 13M13578
Table III.2 Para III.5
Para III.4

FUNCTIONAL DESCRIPTION:

Container consists of an angle iron framed metal base plate with center located satellite south pole quick disconnect support and restraining socket. The design shall include a removeable double bag cover capable of maintaining a clean environment for the satellite assembly. The bag shall allow for penetration and seal of an installed hoist and lift trunnion fitting. The forward shipping support and restraint device includes a metal standoff that captures and restrains the forward hoist and lift trunnion fitting and is bolted to the base plate. The free ends of the encapsulation bag afford final sealment when the forward shipping restraint is bolted to the angle iron base plate. A wooden top completes the shipping container. Each container's metal base plate shall have two channel irons that provide for forklift supports.



NOMENCLATURE:

Handling Beam Assembly
30M20467

DESIGN SOURCE:

In-House

PURPOSE:

To allow for satellite axis change required during dynamic balance operation.

SUPPORTING ACTIVITY:

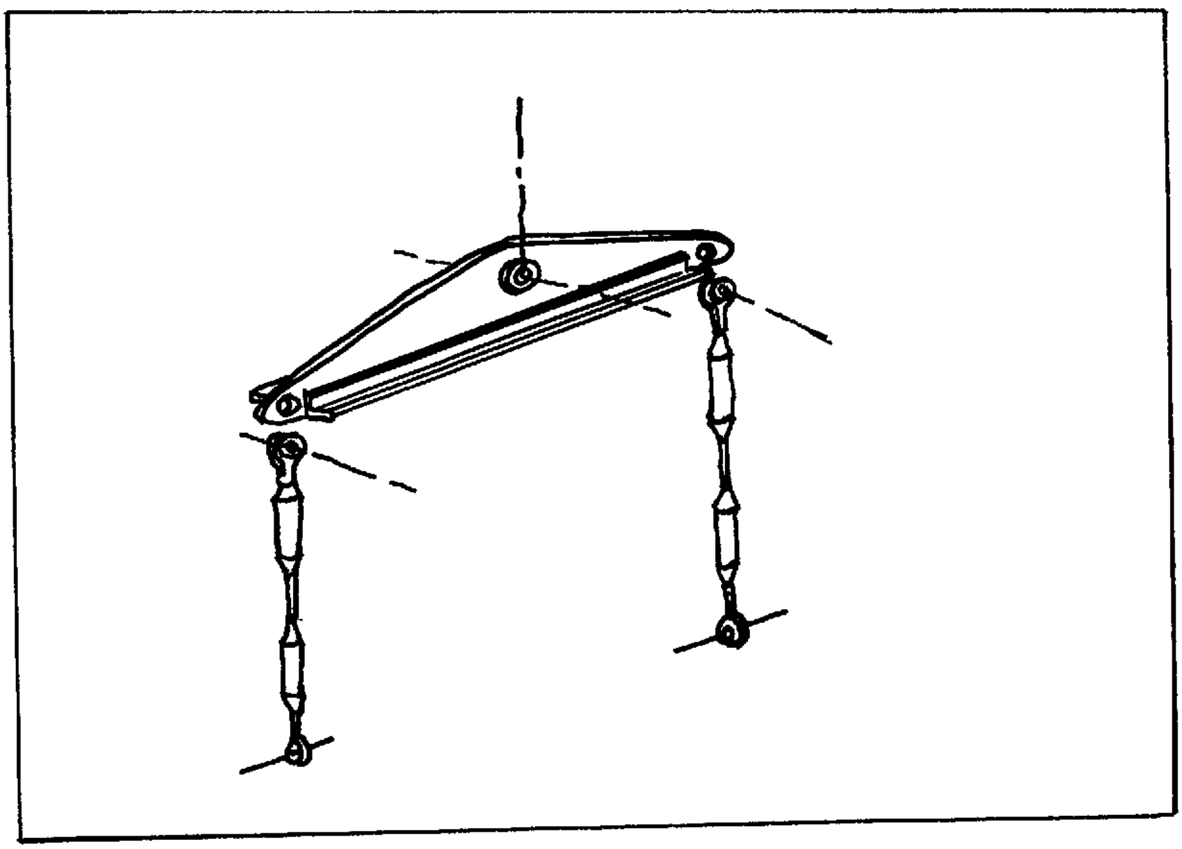
Dynamic Balance Facility

TECHNICAL REFERENCE:

Derived

FUNCTIONAL DESCRIPTION:

A fabricated steel handling beam facility with attendant drops that interface into the satellite support fittings to complete the system. The trunnion interface fitting facilitates rotation of the satellite axis necessary for the dynamic balance operation.



NOMENCLATURE:

LAGEOS CCR and CCR Mount
Installation Tool Kit

DESIGN SOURCE:

In-House

PURPOSE:

Provides installation personnel with proper tools to negotiate CCR installation on the satellite assembly.

SUPPORTING ACTIVITY:

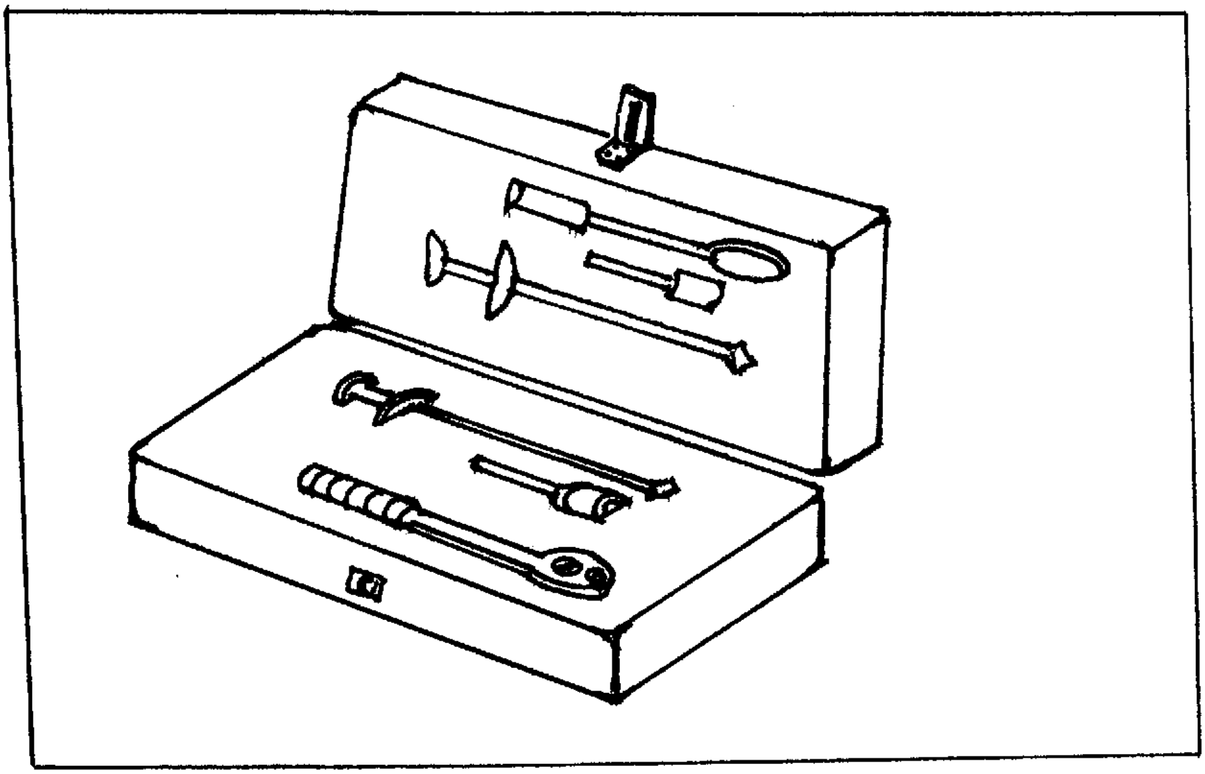
Bldg 836, Laboratory No. 2
Cleanroom, CCR Mount Fit Check

TECHNICAL REFERENCE:

Derived

FUNCTIONAL DESCRIPTION:

A Phillips Head Screwdriver Bit Socket and automatic micro adjusting type torque wrench to install the CCR mounting screws into the LAGEOS satellite. A mechanical fingers device will be used to handle each CCR during the installation phase. The tools will be kitted in a formed fitted box to sustain their cleanliness.



NOMENCLATURE:

LAGEOS CCR
Installation Stand

DESIGN SOURCE:

In-House

PURPOSE:

Supports and allows satellite to be transferred to the cleanroom and undergo the 2968 separate operations required to mount the CCR subassemblies.

SUPPORTING ACTIVITY:

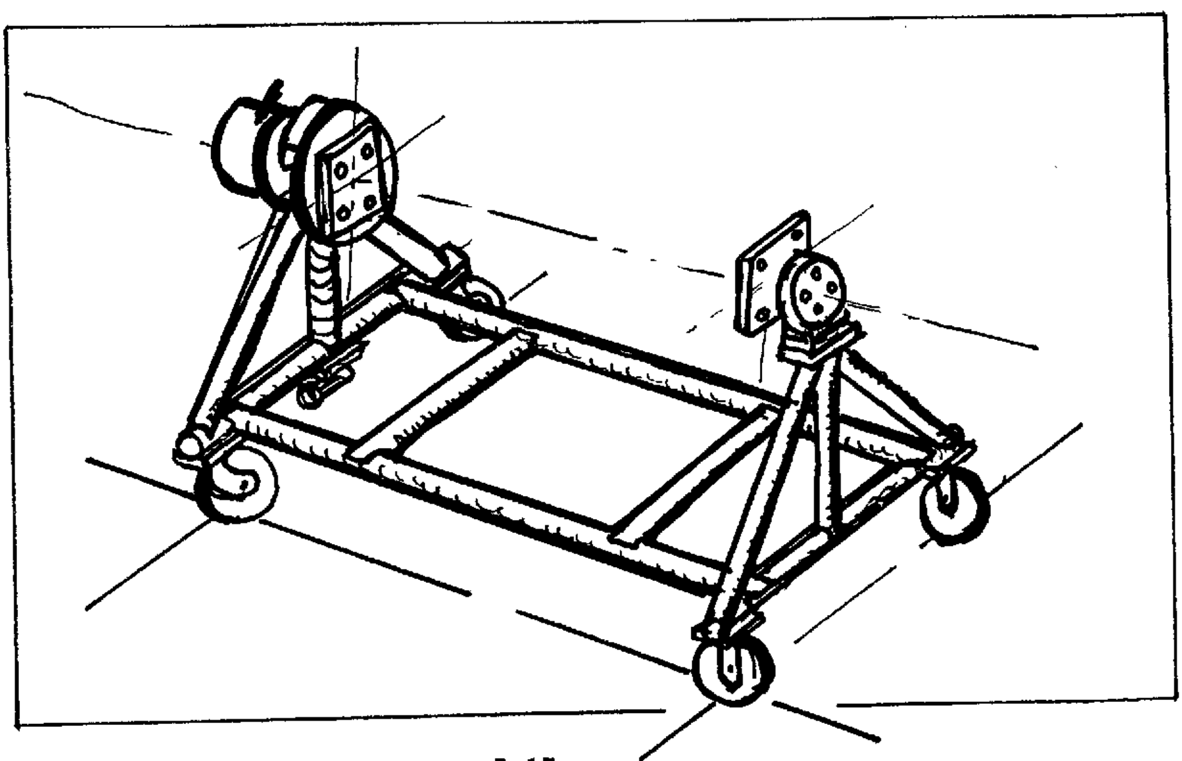
Bldg 836, Laboratory No. 2
Cleanroom

TECHNICAL REFERENCE:

Derived

FUNCTIONAL DESCRIPTION:

An installation stand, that supports the satellite to a working height convenient to the CCR installation personnel. The stand is equipped with caster type wheels to allow the assembly to be positioned into and out of the cleanroom. The basic stand is an existing Saturn S-IC stage propellant valve checkout and handling stand adapted to satisfy LAGEOS CCR installation requirements. The satellite w/special adapter plates interfacing with the existing stand plates provides for the satellite support. The stand has trunnion bearings, rotation lock system, and brake features.



APPENDIX B

SUPPORT EQUIPMENT LIST

LAGEOS Support Equipment List

Wood Storage Box, 30"x30"x34"

LN_2 Cooling Container

Support Fitting, 30M20462, 4 each

LAGEOS Balance Weights, 30M20469, 96 pieces

3/4" Lifting Eye Bolt, 2 each

Optical Alignment Pin

Threaded Adapters, 30M20465, 2 each

Threaded Adapters, 30M20464, 2 each

Lifting Bolts

Wooden Table, 21 Inch Hole, 36"x36"x32"

Wood Storage Rack, 12"x26"x32"

Steel Fly Cutter

Lathe Mandrel - Aluminum

Assembly Guide-Lifter (Alum)

LAGEOS CCR and CCR Mount Installation Tool Kit

LAGEOS CCR Installation Stand

LAGEOS Shipping Container

LAGEOS Inertial Weight Handling Fixture

Balance Test Fixture, 30M20461

Satellite Assembly Fixture

Lifting Eye, 30M20466

Handling Beam Assembly, 30M20467

8.0 QUALITY AND RELIABILITY ASSURANCE ACTIVITIES

8.1 Verification

8.1.1 Development/Qualification Test Support

Development testing, which might later be used to qualify the design of the satellite or Cube Corner Reflectors (CCR's) for flight worthiness, was verified by Reliability and Quality Assurance personnel. Two test programs were in this category.

Six CCR's mounted in an aluminum block were tested at Bendix Aerospace Systems DW, Contract NAS8-30658, to assure the optical quality and verify the mounting of the CCR's under thermal/vacuum and mechanical vibration levels expected during the mission. Test facilities, procedures, and operations were verified by MSFC Quality Assurance personnel.

A development test satellite was fabricated at MSFC. The satellite was inspected during fabrication and assembly and an Inspection Report completed. Following fabrication, a spin balance test was performed on the satellite. Quality personnel verified test and handling facilities, test fixtures, concurred in test procedure, verified test operations. All activities were evaluated to assure safety of satellite and personnel. Quality personnel, then, verified the transfer of the satellite from the test site to bonded storage.

8.1.2 Acceptance Test Support

Perkin-Elmer was selected to fabricate the CCR's. The Quality Assurance Plan, DR-TM-01, DPD No. 448, has been evaluated and approved. DCAS has been delegated to perform the Quality Assurance functions at Perkin-Elmer. However, personnel from the Reliability and Quality Assurance Office will verify acceptance test of the Cube Corner Reflectors.

8.2 Specification Support

Quality Assurance requirements were developed for LAGEOS Satellite Structure Detail Specification and for the Contamination Control Plan.

At the Satellite Structure Preliminary Design Review, the Satellite Structure Detail Specification, Contamination Control Plan, Satellite-Adapter Interface, Manufacturing, Handling, Shipping Operations, and the results from the Development Satellite Spin/Balance Test were reviewed. The review indicated the development test satellite met the design specifications.

9.0 Specifications

During the Phase B portion of the LAGEOS Satellite program, several documents were originated to define the requirements. These documents served as the project definition for the Phase B studies. The primary documents which served this purpose are listed below:

ES-LA-100	Performance and Design Requirements for the LAGEOS Project
13M13578	LAGEOS to Delta Launch Vehicle Interface Control Document
68M00037	LAGEOS Test Requirements Document
CCR-1	Corner Cube Retroreflector Detail Specification.
SAT-1	LAGEOS Satellite Structure Detail Specification

Design changes were implemented as the Phase B studies progressed. One of the significant changes was the location of the CCR's on the satellite sphere. Revision A to the ICD incorporated this change. Other areas changed such as the preferred moment of inertia and the launch vehicle spacecraft adapter design and the interface to the LAGEOS Satellite. A revision to the LAGEOS ICD will incorporate these changes. A formal means of controlling baselines and changes to baseline documentation was presented to the preliminary design review board. This computer tracking system will be utilized in Phase C/D to track changes and update documentation.

A specification was originated during Phase B and presented to the PDR. This specification, SAT-1, reflects the fabrication and verification requirements of the LAGEOS Satellite structure.

10.0 References

1. The Smithsonian Earth Physics Satellite (SEPS), NASA TM X-64632, dated September, 1971.

2. Performance and Design Requirements for the LAGEOS Project, ES-LA-100, dated January 24, 1974.

3. Bendix Test Report No. BSR 4159, dated October, 1974.

4. LAGEOS Interface Control Document, 13M13578

5. LAGEOS Satellite Structure Detail Specification, SAT-1, dated January 17, 1975.

6. LAGEOS Satellite Assembly Drawing, 30M20460.

7. LAGEOS Hemisphere Drawing, 30M20459.

8. LAGEOS Lifting Eye Drawing, 30M20466.

9. LAGEOS Handling Beam Assembly Drawing, 30M20467.

10. LAGEOS Shipping Container Drawing, 30M20471.

11. Corner Cube Retroreflector Drawing, 50M24461.

APPROVAL

LAGEOS PHASE B TECHNICAL REPORT

The information in this report has been reviewed for security classification. Review of any information concerning Department of Defense or Atomic Energy Commission programs has been made by the MSFC Security Classification Officer. This report, in its entirety, has been determined to be unclassified.

This document has also been reviewed and approved for technical accuracy.

APPROVED:

Lewis L. McNair
LAGEOS Chief Engineer

James E. Kingsbury
Associate Director for Engineering
Science & Engineering

Richard G. Smith
Director
Science & Engineering

CONCURRENCE:

Charles W. Johnson

for Donald R. Bowden
LAGEOS Task Team Manager

James T. Murphy
Director
Program Development

☆U.S. GOVERMENT PRINTING OFFICE 1975–640-452/237 REGION NO. 4

DISTRIBUTION

INTERNAL

DA01
Dr. Lucas

DS01
Dr. Stuhlinger

PP01
Mr. Sneed

PD01
Mr. Marshall

PS01
Mr. Gierow

EA01
Mr. Smith

PA01
Mr. Murphy

EE01
Mr. Kingsbury
Mr. McNair (6)

PF03
Mr. Bowden
Mr. Johnson (6)

EC01
Mr. Moore

EC31
Dr. Randall

ED01
Dr. Lovingood

ED21
Mr. Ryan

ET01
Mr. Reinartz

ET11
Mr. Connor

ET32
Mr. Jones

AT01
CC01

EP01
Mr. McCool

EP41
Mr. Hopson

EP11
Mr. Kroll

EP13
Mr. Lysaght

EG01
Mr. Brooks

EG01
Ms. Folsom

EH01
Mr. Schwinghamer

EL52
Mr. Aberg
Mr. Johnson

EC32
Mr. Zurasky

ED24
Mr. McBride

ET12
Mr. Moseley

EP43
Mr. Creel

EP13
Mr. Harrison

ED22
Mr. Admire

ET15
Mr. Eoff
Mr. Allen

EL22
Mr. Moore

AS61
AS61L (8)

EXTERNAL

NASA Headquarters
Code OA/ES/Mr. Williams
Code OA/ES/Mr. Spencer

Smithsonian Astrophysical Observatory
Cambridge, Massachusetts 02138
Dr. G. C. Weiffenbach
Mr. T. E. Hoffman
Dr. Dave Arnold
Mr. Watts

Bendix Corporation (2)

Zygo Corporation (2)

ITEK Corporation (2)

MDAC (West) (2)

Goddard Space Flight Center (3)

John F. Kennedy Space Center (2)
(WTR)

Scientific and Technical Information
Facility (25)
PO Box 33
College Park, Maryland 20740
Attn: NASA Representative