Laser Geodynamic Satellite Thermal/Optical/Vibrational Analyses and Testing

Final Report

Volume I
Executive Summary

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Contract NAS 8-30658

October 1974

Prepared for:

George C. Marshall Space Flight Center
National Aeronautics and Space Administration
Marshall Space Flight Center, Alabama 35812

Bendix Aerospace Systems Division

Ann Arbor, Michigan

BSR 4159

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FOREWORD

This technical report presents the results of the LAGEOS Phase B Thermal/Optical/Vibrational Analyses and Test Program. The study was conducted by the Bendix Corporation, Aerospace Systems Division for the National Aeronautics and Space Administration, George C. Marshall Space Flight Center, under Contract NAS 8-30658.

The results of this study are contained in two volumes, which are prepared and submitted in accordance with the data requirements of Contract NAS 8-30658, as follows:

Volume I   Executive Summary

Volume II   Technical Report

The study program was initiated in January 1974, the technical effort was completed in September 1974 and the final report was completed in October 1974. The effort was conducted under the direction of Mr. D. R. Bowden, LAGEOS Program Manager, and Mr. C. W. Johnson of the LAGEOS Program Office, NASA-MSFC, Code PD-LA-MGR.

The successful and timely completion of these analyses and test efforts is attributed to the conscientious and devoted efforts of J. Zurasky, R. Creel and C. W. Johnson of NASA/MSFC and E. Granholm, J. Maszatics, J. Monroe and L. Lewis of Bendix, under the direction of J. Brueger, Bendix Program Manager. The essential cooperation and assistance of P. Forman, C. Zanoni, S. Laufer and W. Fox at Zygo Corporation in Middlefield, Connecticut (retroreflector fabrication, Far-Field Diffraction Instrument development and test program support) and, of M. Kahan, M. Rimmer, D. Byrd and J. Mieron at the Optical Systems Division, Itek Corporation in Lexington, Massachusetts (retroreflector thermal/optical analyses) are also gratefully acknowledged.

VOLUME I

CONTENTS

VOLUME I

LIST OF TABLES

LIST OF ILLUSTRATIONS

VOLUME I

1.0 INTRODUCTION

This report documents the results of the LAGEOS Thermal/Optical/Vibrational Analyses and test program (Contract NAS 8-30658), conducted for the National Aeronautics and Space Administration, George C. Marshall Space Flight Center from January through September 1974. The purpose of this study is to verify, through analysis and test, that the MSFC LAGEOS design inherently provides a retroreflector thermal environment which maintains acceptable retroreflector internal thermal gradients. Acceptable thermal gradients are those which result in less than 50% degradation of optical performance from isothermal optical performance.

This volume provides an executive summary of the study program, as required and defined by the documentation requirements (DR No. MA-04, DPD No. 296) of Contract NAS 8-30658. It summarizes the study objectives, the study approach, the principal assumptions, the type of basic data generated and the significant results. It briefly identifies the other NASA and NASA-funded related efforts. Reference is made to Volume II for detail data in describing the generated data and results. The study limitations, implications for research and suggested additional efforts are also summarized.

2.0 STUDY OBJECTIVES

The overall objectives of the LAGEOS Thermal/Optical/Vibrational Analyses and Test Program, to meet the study purpose of LAGEOS design verification in the satellite flight/orbital environment, are summarized as follows:

- Develop a LAGEOS thermal model and conduct thermal analysis, using this model, to predict retroreflector thermal behavior.
- Procure and fabricate test hardware required to simulate the LAGEOS design for the purpose of conducting environmental tests.
- Accomplish thermal, optical, and mechanical vibration tests to verify that the thermal model and thermal analysis predictions are representative of actual satellite performance.

These objectives and the detailed tasks to be accomplished to meet these objectives are described in greater detail in the Program Study Plan, (reference A).

3.0 RELATIONSHIP TO OTHER NASA EFFORTS

This study and its objectives are intended to support the overall NASA-MSFC LAGEOS Program. The other related NASA efforts are the LAGEOS design/fabrication effort at MSFC, the system evaluation effort at Smithsonian Astrophysical Observatory, the launch vehicle integration effort at GSFC/McDonnell Douglas Astronautics Company (West), and the LAGEOS Phase C/D retroreflector fabrication/test effort at the Electro-Optical Division of the Perkin-Elmer Corporation. The analytical and test data generated in this study,and the Bendix participation at various program interface and review meetings during this study effort, have contributed to the support of these related NASA efforts.

4.0 METHOD OF APPROACH AND PRINCIPAL ASSUMPTIONS

4.1 Method of Approach

The study objectives were met by the accomplishment of three major tasks which were intended to provide the required technical results. These tasks, defined in greater detail in the Program Study Plan (reference A), are as follows:

- Task 1 - Develop Thermal Model and Perform Thermal Analysis. This effort included development of a LAGEOS thermal math model, parametric analysis and final satellite temperature predictions, after correlation of the model with thermal test results. This effort also included thermal/optical analysis at the Itek Corporation to predict optical performance of the retroreflector under various thermal conditions. The early analysis effort supported the selection of the final LAGEOS retroreflector design.

- Task 2 - Provide the LAGEOS Test Article. This effort included the procurement of six (6) LAGEOS retroreflectors from the Zygo Corporation and the design, fabrication and assembly of a test article to represent the LAGEOS design, for use in the thermal/optical and vibration tests in the program. It also included a thermocouple fixture, instrumented to provide temperature measurement data from the tests.

- Task 3 - Conduct Thermal/Optical and Vibration Tests. This effort included the generation of a test plan and test procedures, fabrication and assembly of various test fixtures, and the set-up and accomplishment of the thermal/optical and vibration tests. This effort also included the evaluation of the test results, a final presentation of the study program results at the MSFC LAGEOS

PDR and the generation of this final report. In addition, this task included the generation of a dynamic model of the initial baseline design and a dynamic analysis to support the selection of the final LAGEOS retroreflector/mount design.

4.2 Principal Assumptions

An initial set of baseline assumptions were defined at the start of the study for the early phase of the study (reference A). As the analysis effort at Bendix and the design effort at MSFC developed results, a final set of baseline assumptions were established. The final principal assumptions are summarized, as follows:

- Spherical satellite configuration is approximately 24 inches in diameter and contains 426 retroreflectors.
- Satellite outside surface is bare machined aluminum.
- Satellite retroreflector cavities are located and designed per MSFC drawing 30M20459 (dated 10 May 1974).
- Retroreflector configuration is the 1.5-inch circular-faced design with three integral mounting tabs, as defined in MSFC drawing 50M24461 (initially Revision C and updated to Revision G).
- Retroreflector mount configuration utilizes a set of KEL-F mounting rings and an aluminum retainer ring, as shown in MSFC drawings 50M23161 (Rev. A), 50M23170 and 50M24459 (Rev. D).
- Satellite orbital conditions:

Altitude:	5900 km
Inclination:	110°
Eccentricity:	0
Spin rate:	0 rpm, the worst-case condition from a thermal-condition standpoint.

5.0 BASIC DATA GENERATED AND SIGNIFICANT RESULTS

5.1 Basic Data Generated

The basic data generated in the various phases of the study program are provided, in detail, in Volume II and its appendices. A brief summary is provided in this section. The final results of the satellite thermal predictions are listed in Table 5-1.

The final results of the thermal/optical analysis by Itek are given in Table 5-2. The description column refers to the dihedral angles and the as-manufactured wavefront deviation of the retroreflector.

The thermal/optical test program conditions are summarized in Tables 5-3a and 5-3b and Figure 5-1. The results are too voluminous to summarize here, but they are provided, in detail, in Volume II and its appendices. A representative set of thermal/optical test results are given in Figure 5-2. The conclusions from the evaluation of this optical test data are summarized in Section 5.2 below. A comparison of the basic retroreflector characteristics,measured prior to the test program,are shown in Table 5-4. A comparison of analysis results and test results, for one retroreflector, are given in Table 5-5.

The vibration tests exposed the LAGEOS test article to the vibration environment shown in Figures 5-3 and 5-4. No damage or significant effect on configuration or optical performance was noted after the test. Details are described in Volume II and its appendices.

5.2 Significant Results

The conclusions resulting from an evaluation of the analyses and test data,generated in this study,are summarized as follows:

- The LAGEOS design demonstrates acceptable performance (less than 50% degradation) under worst-case orbital thermal conditions.
- No significant thermal/optical performance degradation results from exposure of the LAGEOS design to the LAGEOS launch/boost vibration environment.
- The nominal dihedral angle (90° 0′ 1.5″), as specified for the LAGEOS retroreflectors, appears to be too large for optimum return intensity within the LAGEOS far-field diffraction pattern annular region (13.2 - 16.9 arc sec diameters).

TABLE 5-1

LAGEOS

SUMMARY OF SATELLITE FLIGHT THERMAL ANALYSIS RESULTS*

LOCATION	RETRO #1 FULL SUN	RETRO #2 45° OFF SUN	RETRO #3 180° OFF SUN	RETRO #4 90° OFF SUN	AVERAGE
RETRO TEMPERATURE	16.0°C	8.5°C	-7.5°C	-2.5°C	3.6°C
ΔT AXIAL	2.5°C	2.2°C	2.1°C	2.3°C	2.3°C
ΔT RADIAL	1.7°C	1.5°C	1.3°C	1.2°C	1.4°C

NOTE: 1. SATELLITE CORE TEMPERATURE = 54.0°C.

2. APPROXIMATE 8°C GRADIENT ACROSS SATELLITE STRUCTURE.

*BARE MACHINED 6061-T6 ALUMINUM SATELLITE AND RETAINER RINGS.

TABLE 5-2

LAGEOS

SUMMARY OF OPTICAL ANALYSIS CASES/RESULTS

CASE	DESCRIPTION	TEMPERATURE GRADIENT	LASER FIELD ANGLE	% RETURN IN ANNULUS (32-41 μ RAD RADII)
2.1	PERFECT; 1.5"	ISOTHERMAL	0°	18.4
2.1	PERFECT; 1.5"	ISOTHERMAL	-15°	9.6
2.2	λ/4; 1.5"	ISOTHERMAL	0°	18.0
2.2	λ/4; 1.5"	ISOTHERMAL	-15°	8.8
2.4.a	λ/4; 1.0", 1.5", 2.0"	ISOTHERMAL	0°	17.7
2.4.a	λ/4; 1.0", 1.5", 2.0"	ISOTHERMAL	-15°	8.6
2.3.a.1	λ/4; 1.5"	ΔTa = 1.0°C, ΔTr = 0.4°C	0°	18.0
2.3.a.2	λ/4; 1.5"	ΔTa = 3.5°C, ΔTr = 2.0°C	0°	17.1
2.3.b	λ/4; 1.5"	ΔTa = 1.9°C, ΔTr = 1.3°C	0°	17.2
2.3.b	λ/4; 1.5"	ΔTa = 1.9°C, ΔTr = 1.3°C	-15°	8.3
2.4.b.2	λ/4; 1.0", 1.5", 2.0"	ΔTa = 1.9°C, ΔTr = 1.3°C	0°	16.9
2.4.b.2	λ/4; 1.0", 1.5", 2.0"	ΔTa = 1.9°C, ΔTr = 1.3°C	-15°	8.1
2.5.a	λ/4; 1.5"	ΔTa = 2.0°C, ΔTr = 0°C	0°	15.9
2.5.b	λ/4; 1.5"	ΔTa = 0°C, ΔTr = 2.0°C	0°	4.2

TABLE 5-3a

LAGEOS

SUMMARY OF THERMAL/OPTICAL TEST CONDITIONS

RETROREFLECTOR ORIENTATION	TEST ARTICLE TEMP.	TEST DESCRIPTION	TEST NO.	POST VIB	NO. OF LASER INCIDENT ANGLES*
$\theta_D = 60$, $\theta_E = 40$, $\theta_F = 20$	AMBIENT	ISOTHERMAL-AMBIENT	10		8
		ISOTHERMAL-VACUUM	11		15 (8)
	-30C THERMAL/VACUUM	NO SUN-NO IR	19		15
	+30C THERMAL/VACUUM	NO SUN-NO IR	12		15
$\theta_D = 60$, $\theta_E = 100$, $\theta_F = 20$	AMBIENT	ISOTHERMAL-AMBIENT	20, 20A	X	15
			23	X	15
		ISOTHERMAL-VACUUM	13	X	15 (8)
	-30C THERMAL/VACUUM	NO SUN-NO IR	21	X	15
	+30C THERMAL/VACUUM	NO SUN-NO IR	14	X	15 (11)
	+60C THERMAL/VACUUM	NO SUN-NO IR	22	X	15

* NO. OF LASER ANGLES:

8 (A, D: α = +30, +15, -30)
B, E: α = +15, 0
C, F: α = 0

15 (A, B, C α = +30, +15, 0, -15, -30)
D, E, F

NOTE:
( ) ORIGINAL PLAN
TEST NO. > 14 ARE ADDED ABOVE ORIGINAL PLAN

BSR 4159

TABLE 5-3b

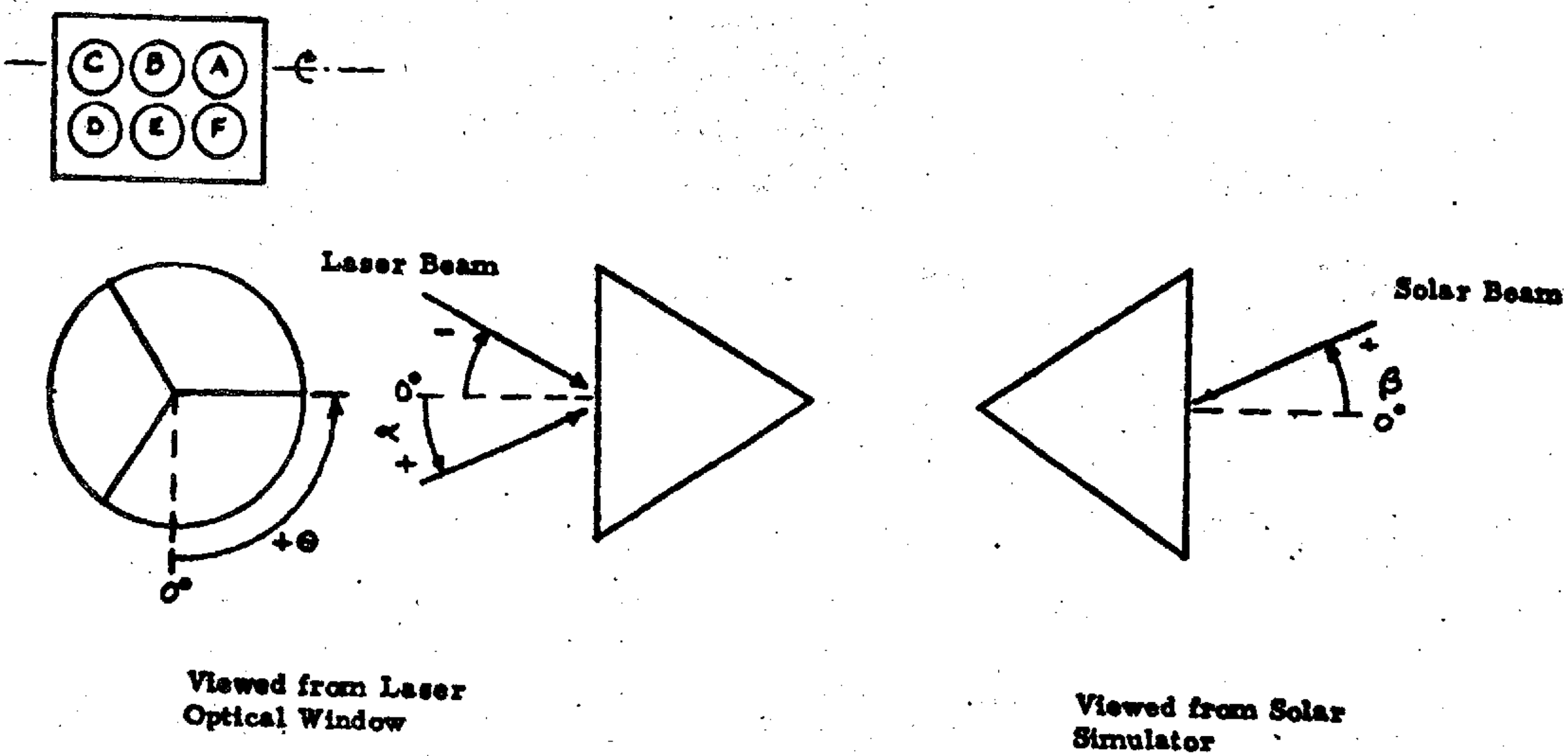
LAGEOS

SUMMARY OF THERMAL/OPTICAL TEST CONDITIONS

RETROREFLECTOR ORIENTATION	TEST ARTICLE TEMP.	TEST DESCRIPTION	TEST NO.	POST VIB	NO. OF LASER INCIDENT ANGLES*
$\theta_A = 0$ $\theta_B = 90$ $\theta_C = 80$	AMBIENT	ISOTHERMAL-AMBIENT	1		8
			15		8
			16		8
			24	X	15
		ISOTHERMAL-VACUUM	2		15
			17		15
			18		15
	-30C THERMAL/VACUUM	NO SUN-NO IR	7		15
		NO SUN-1 EARTH IR	9		8
		1 SUN-NO IR	8		8
	+30C THERMAL/VACUUM	NO SUN-NO IR	3		15
		NO SUN-1 EARTH IR	6		8
		1 SUN-NO IR	4		8
	+60C THERMAL/VACUUM	NO SUN-NO IR	5		15 (8)

BSR 4159

FIGURE 5-1



SOLAR AND LASER FIELD ANGLES AND RETROREFLECTOR ORIENTATION

FIGURE 5-2

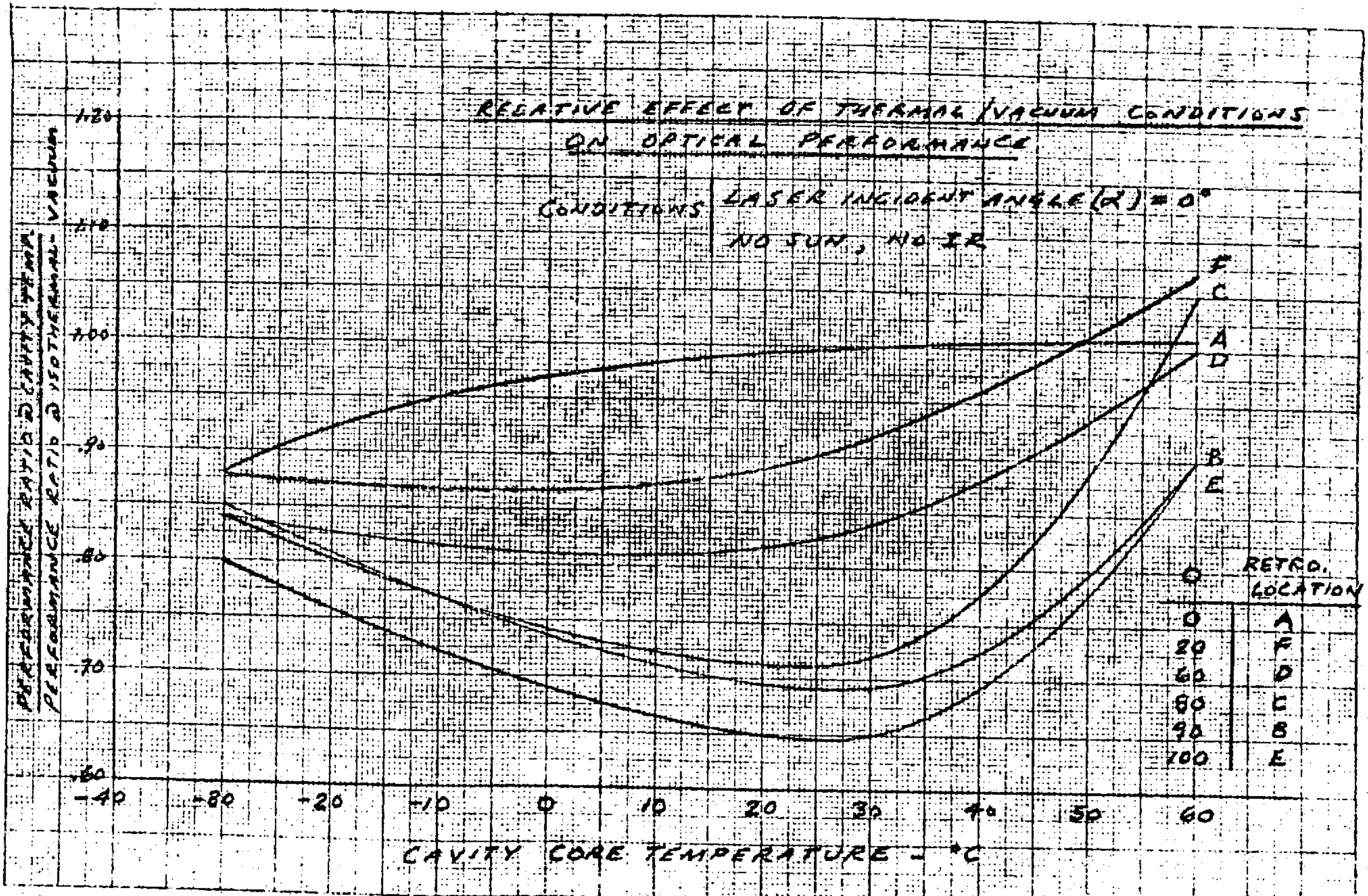

RELATIVE EFFECT OF THERMAL/VACUUM CONDITIONS ON OPTICAL PERFORMANCE
CONDITIONS: LASER INCIDENT ANGLE (α) = 0°
NO SUN, NO IR
PERFORMANCE RATIO @ CAVITY TEMP. / PERFORMANCE RATIO @ ISOTHERMAL-VACUUM
CAVITY CORE TEMPERATURE - °C
F
C
A
D
B
E
RETRO. LOCATION
θ
0 A
20 F
60 D
80 C
90 B
100 E

TABLE 5-4

LAGEOS RETROREFLECTOR CHARACTERISTICS

TEST LOCATION		A	B	C	D	E	F
SERIAL NO.		3	5	6	1	4	2
WAVEFRONT DEVIATION							
SECTOR	1	0.15 λ	0.10 λ	0.10 λ	0.20 λ	0.20 λ	0.20 λ
	2	0.15	0.20	0.12	0.15	0.10	0.15
	3	0.10	0.10	0.10	0.10	0.20	0.17
	4	0.10	0.10	0.10	0.12	0.15	0.20
	5	0.10	0.10	0.10	0.10	0.15	0.10
	6	0.10	0.10	0.15	0.15	0.20	0.20
DIHEDRAL* ANGLES (ARC SEC)							
$R_1 - R_2$		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
DIAMETER OF ANNULUS CENTROID (ARC SEC)**		17.6	23.5	18.4	22.0	20.6	19.8

*90° + Angle Tabulated

**Based on Far-Field Pattern Photograph Measurement

TABLE 5-5

LAGEOS

COMPARISON-THERMAL/OPTICAL ANALYSIS AND TEST RESULTS

	THERMAL/OPTICAL ANALYSIS	THERMAL/OPTICAL TEST
RETROREFLECTOR	MATH MODEL	A (SERIAL NO. 3)
DIHEDRAL ANGLES (ARC SEC)	1.0, 1.5, 2.0	1.81, 1.08, 1.42
WAVE FRONT DEVIATION OF EACH SECTOR	.25λ	0.15λ, 0.15λ, 0.10λ 0.10λ, 0.10λ, 0.10λ
DIAMETER OF FFDP CENTROID (ARC SEC)	16.5	17.6
DATA ANNULUS DIAMETERS (ARC SEC)	13.2 - 16.9	13.2 - 16.9
ISOTHERMAL-VACUUM ANNULAR RETURN / FULL FIELD RETURN	.177 (α = 0) .086 (α = -15°	.124 α = 0 .084 α = -15°
THERMAL-VACUUM ANNULAR RETURN / FULL FIELD RETURN	.169 (α = 0) .081 (α = -15°)	.135 (α = 0) .102 (α = -15°)
ΔT AXIAL (°C)	1.9	*
ΔT RADIAL (°C)	1.3	*
CAVITY CORE TEMPERATURE	+30°C	+30°C (1 SUN-NO IR)

*DATA UNKNOWN

FIGURE 5-3

LAGEOS
SINUSOIDAL VIBRATION

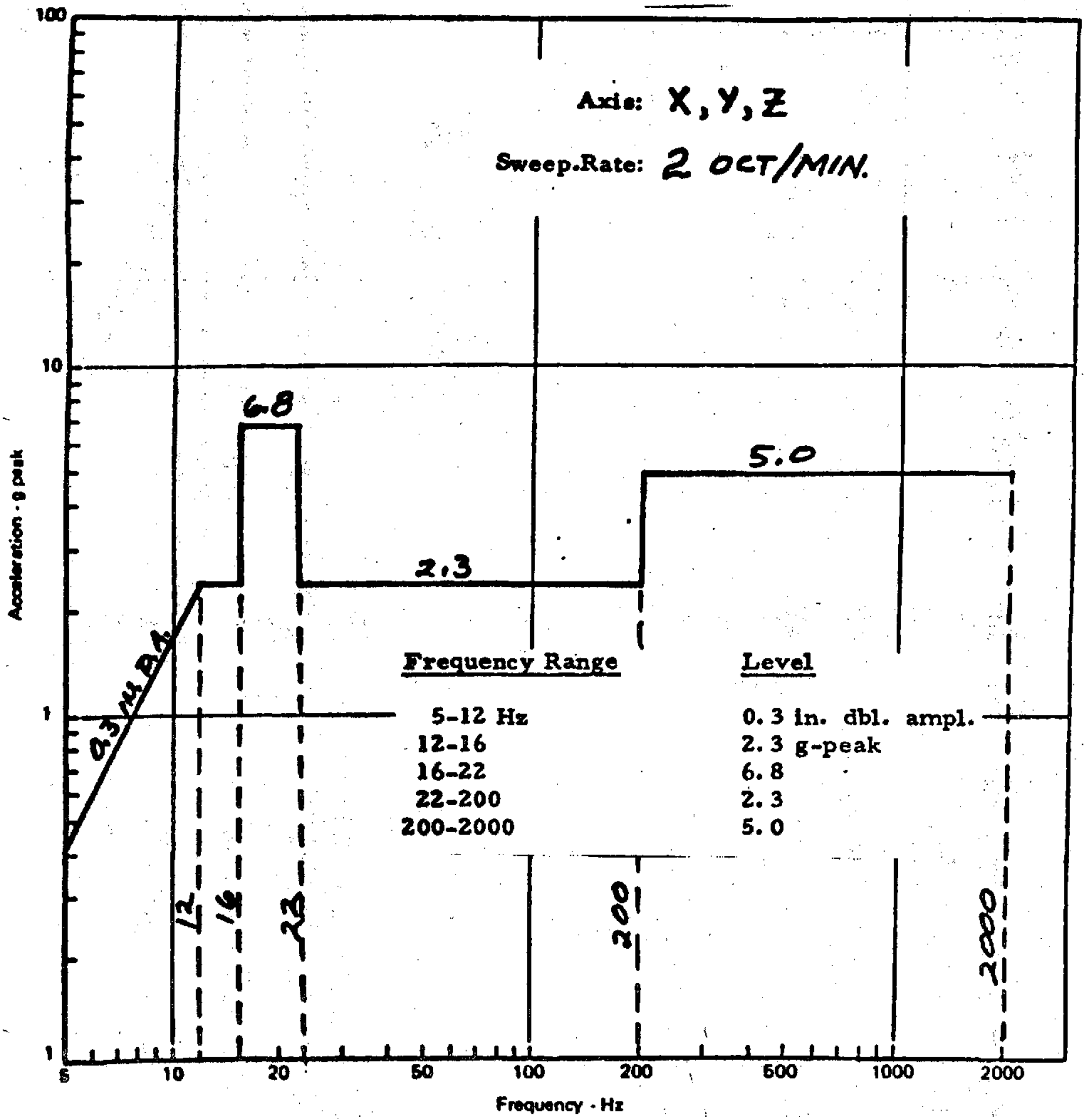
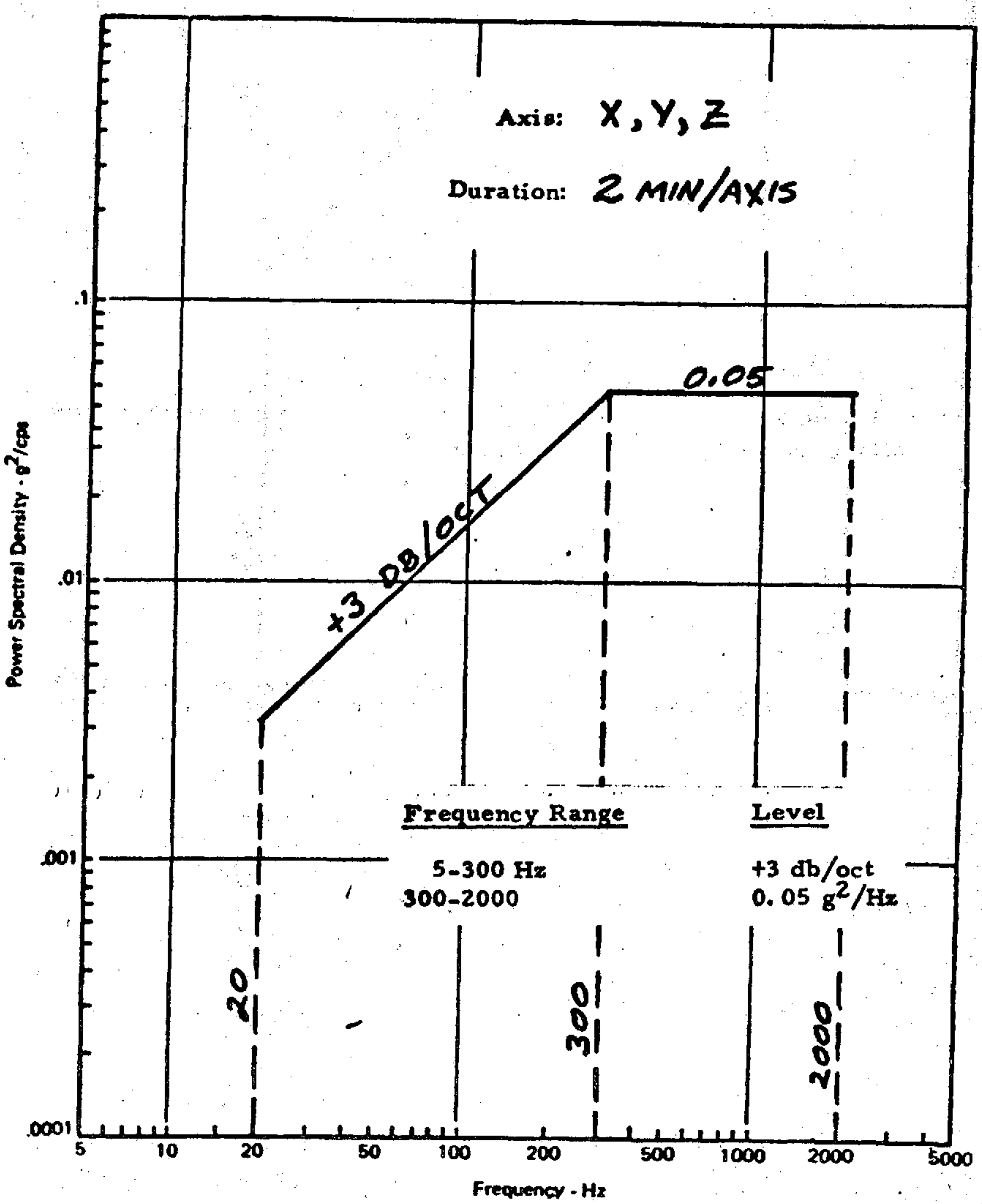


FIGURE 5-4

LAGEOS

RANDOM VIBRATION SPECTRUM



Frequency Range	Level
5-300 Hz	+3 db/oct
300-2000	0.05 g^2/Hz

- The present dihedral angle tolerance ($\pm 0.5''$) results in relatively large optical performance differences between individual retroreflectors.

- The LAGEOS launch/boost acoustic environment is negligible, compared to the vibration environment; therefore, it is concluded that no effect on LAGEOS thermal/optical performance will result from exposure to the acoustic environment.

- The close agreement, between thermal predictions and thermal test results (within $5^{\circ}C$), provides confidence that satellite thermal gradients are accurately predicted by the LAGEOS thermal model.

- Based on thermal/optical analysis results, it is concluded that optical performance is relatively insensitive to irregular dihedral angle tolerances (i.e., angles distributed on each side of the nominal angle) and manufactured surface quality effects; optical performance varies considerably when dihedral angles change in the same direction from 1.5 arc sec nominal (i.e., relative performance changes from 21.6% to 14.9% for a +0.6 arc sec dihedral angle change).

- Thermal/optical performance varies only about 1% in relative performance for the range of thermal gradients evaluated in the thermal/optical analysis.

- Thermal/optical performance is sensitive to individual unit thermal gradients (i.e., only axial gradients or only radial gradients), but axial gradients compensate for radial gradients and for manufactured surface quality effects.

- The LAGEOS thermal model, based on the LAGEOS orbital characteristics and final design parameters and updated by the results of the thermal/optical tests, will provide detail satellite temperature distributions. (A description of the final satellite thermal model, including nodal, resistive and heating information, in both tabulated data format and as a computer deck, have been provided to MSFC.)

6.0 STUDY LIMITATIONS

The study was limited to the accomplishment of the tasks identified in the Study Plan (reference A). Based on the results of the study, they were found adequate to accomplish the overall objectives set forth at the start of the study, as described in Section 2 and defined in the Program Study Plan (reference A).

The number of test conditions actually run in the thermal/optical tests went beyond those defined in the Study Plan, but were accomplished within the available program resources and schedule.

7.0 IMPLICATIONS FOR RESEARCH

The availability of the LAGEOS retroreflectors, with the necessary Bendix test equipment and, in particular, the Far-Field Diffraction Instrument, permits additional testing of retroreflectors to be performed for the purpose of better understanding the effects of various parameters on optical performance. Such additional test results and conclusions would be expected to be of use in the initial identification, feasibility study, and preliminary design of other laser-retroreflector space applications.

8.0 SUGGESTED ADDITIONAL EFFORT

The following summarizes the recommended additional effort as identified in the evaluation of the study results:

- Evaluate the feasibility of retroreflector dihedral angle tolerance specification reduction to obtain more uniform performance (retroreflector-to-retroreflector) and for some performance improvement (if the nominal angle is optimized).

- Re-verify the measured dihedral angles for each test retroreflector and analytically determine the "effective" dihedral angles from Twyman-Green interferograms; confirm the performance improvement in optical tests of the test retroreflectors, after rework of the retroreflectors to the optimum dihedral angles, as selected on the basis of analysis and test data evaluation.

- Perform additional thermal/optical analysis and test efforts to more fully explore the effects of various retroreflector and laser design parameters, in support of additional retroreflector performance data input requirements for the LAGEOS system application analysis at SAO. (Such effort may also be applicable to other programs, as noted in Section 7.0 above.)

- Correlate the Itek thermal/optical math model with the actual retroreflector characteristics, based on Twyman-Green interferogram analysis, with the measured thermal/optical test conditions and with the SAO optical analysis model; generate new thermal/optical performance predictions.

9.0 REFERENCES

The references for this volume are as follows:

A. Study Plan - Laser Geodynamic Satellite Thermal/Optical/Vibrational Analyses and Testing, Bendix Document LAGEOS-8, Revision B, dated 28 June 1974.