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Final Technical Report

NASA Grant 44-005-085

"THE EFFECT OF GRAVITATIONAL FIELDS ON THE POLARIZATION OF ELECTROMAGNETIC SIGNALS"

NASA Grant 44-005-085

A report for the period
September 1, 1969 to August 31, 1970

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Introduction

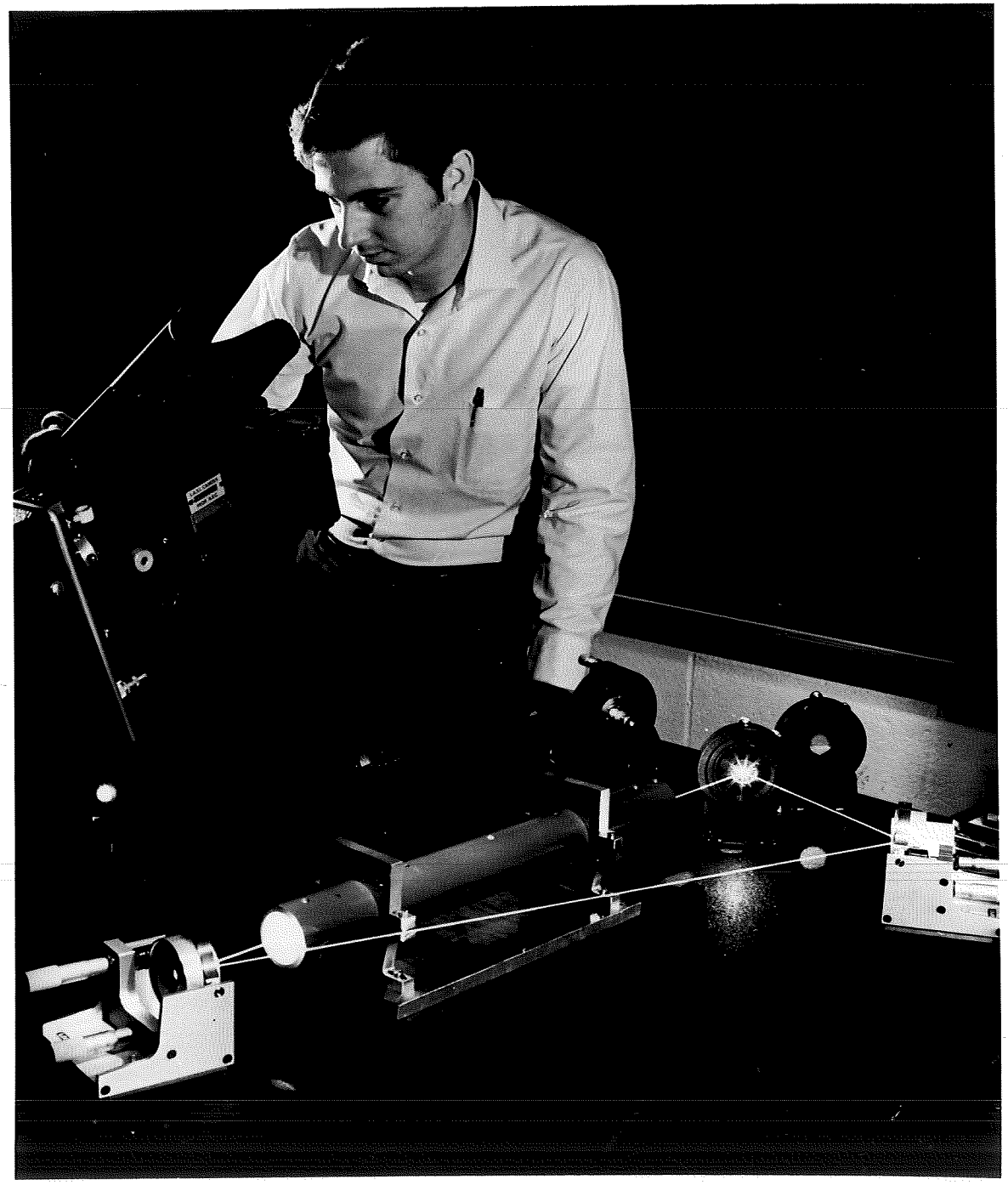
This report summarizes the work that has been accomplished during Phase I of the proposal "The Effect of Gravitational Fields on the Polarization of Electromagnetic Signals," at the University of Houston during the period from September 1, 1969 to August 31, 1970. This work was supported by the NASA Grant 44-005-085.

Summary

The statement of work for the original proposal (see Appendix A) described as a preliminary task the construction of a propagation-direction degenerate, ring laser system. This task was accomplished and produced essential techniques for optical alignment necessary to the work described below. Figure 1 is a photograph of such a ring laser system in operation.

The primary task of Phase I was the construction of a polarization degenerate laser apparatus. This task was accomplished and both states of optical polarization were successfully detected. An experimental apparatus to measure the Cotton-Mouten effect was designed, and its utilization in the polarization degenerate apparatus is pending. However it was discovered that stress induced birefringence in a fused quartz disc could more practically be studied, both

Figure 1 Ring Laser in Operation

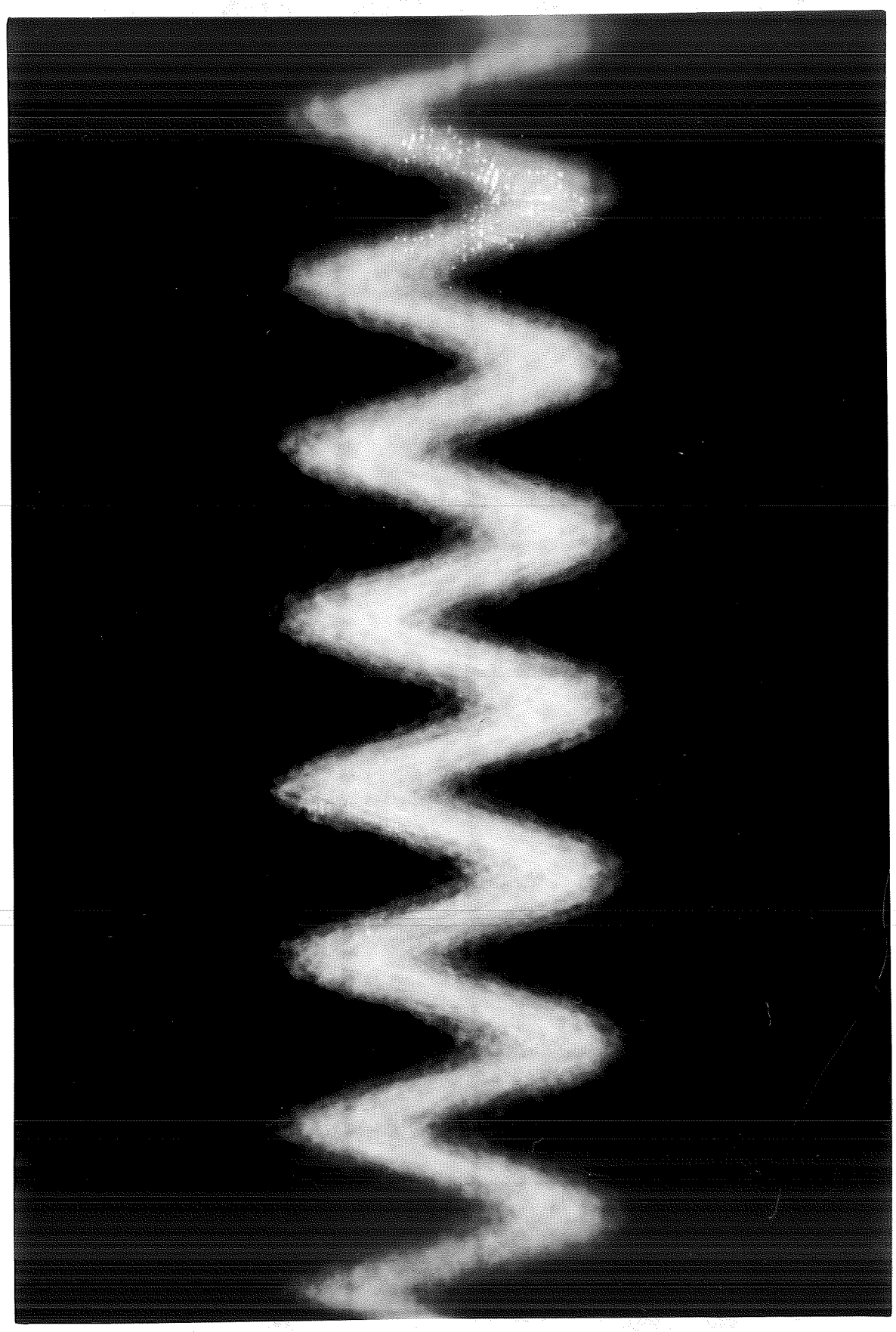


experimentally and theoretically, and such techniques were used to more rapidly develop the polarization degenerate technology. Briefly, if a piece of stressed fused silica is inserted into the initially polarization degenerate optical cavity, the induced birefringence removes the degeneracy of the two optical polarization states; a heterodyning of the two different optical frequencies produces a beat signal proportional to the induced stress. The experimental results of such an investigation, as well as a theoretical analysis, are included in Appendix B. Also see Figure 2.

As an applied spin-off, such a device, as described above, can be used as an absolute gravity meter. If the stability of the laser system can be maintained at its thermal noise limit of $\sim 10^{-3}$ hertz, then in principle, with the apparatus mentioned above, it would be possible to measure a gravitational field to better than one part in 10^9. A small, lightweight, flyable, 10^{-6}g meter <u>with wide dynamic range</u> might be developed from such technology. It is suggested that a portion of the Phase II effort be devoted to a more detailed investigation of this g-meter application.

As mentioned in the original statement of work, Phase II of the proposal would be primarily devoted to the simultaneous excitation and detection of the quadrature signals from the four propagation and polarization states permitted within an optical cavity. Preliminary experimental work appears to have

Fgure 2 A beat signal observed between two once degenerate polarization states in a linear cavity. See Appendix B.



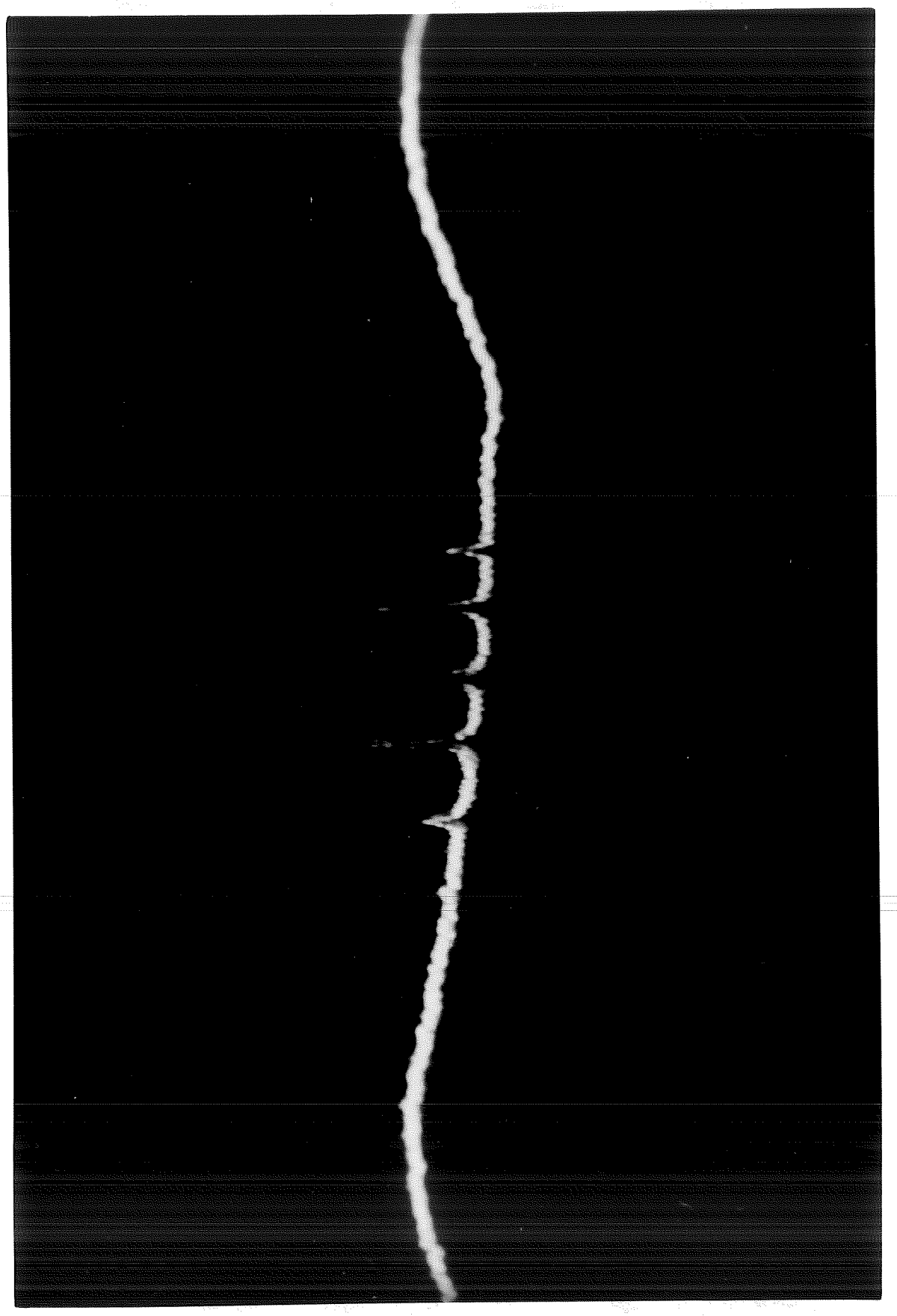
verified the possibility of simultaneous exciting all four modes of propagation within a single re-entrant (ring) optical cavity. The quadrature signals have yet to be detected in a quantitative manner, but their qualitative existence was established at the end of this reporting period. See Figure 3.

Experimentally, it appears that there exists a cavity gain - aperature - ring diameter relationship which prohibits the use of the first design laser discharge tubes in the visible red in ring geometry. Only operation in the infra-red has been achieved to date for the polarization degenerate ring geometry. Second generation discharge tubes will be designed with greater lengths and larger bore diameters to overcome this aperature-gain problem, and quantitative measurements of the quadrature signals will be accomplished in Phase II.

In addition to the experimental effort, an allied theoretical program investigating the propagation of polarized signals in non-inertial frames (gravitational fields) has been initiated. The preliminary effort is summarized in Appendix C.

In conclusion, the essential features of the first phase of the proposal, that is, to prove that four states of optical resonance can simultaneously exist within an optical cavity has been established. If funding continues, the Phase II objectives will be accomplished in the next reporting

Figure 3 Alternate spikes represent different polarization states of a single propagation mode as observed in a triangular ring laser cavity.



period. A statement of work and a budget estimate for Phase II are included in Appendix D.

This work serves as a portion of the requirements for the Ph.D. degree being sought by the candidates, Virgil Sanders, and Ronald Borochoff, at the University of Houston. In addition this work was reported to the Texas Academy of Sciences, San Angelo meeting, March 5, 1970.

APPENDIX A: INITIAL STATEMENT OF WORK NASA Grant 44-005-085

The essential features of the proposal are to prove the principle that four states of optical resonance can simultaneously exist within an optical cavity, and to develop an apparatus with sufficient stability and sensitivity to measure the beat frequencies between these co-existing states when the degeneracy between them is lifted by means of some acceleration gravitational field.

A preliminary task will be to construct and put into operation a propagation-direction degenerate, "ring-laser" system and its associated beat frequency electronics, capable of detecting the removal of the propagation direction degeneracy.

The primary task of Phase I will be to construct and put into operation a polarization-degenerate laser apparatus and simultaneously excite and detect both polarization states within the optical cavity. A study of the Cotton-Mouten effect (birefringence proportional to the square of the applied magnetic field strength) will be utilized to simultaneously develop the polarization-degenerate technology, and to yield useful scientific data as an aside.

The development of the polarization degenerate apparatus and its associated technology will lead into the second phase goal of simultaneously exciting and detecting the four

quadrature signals between the two states of polarization and the two states of propagation permitted theoretically within an optical ring cavity.

APPENDIX B POLARIZATION DEGENERATE LASER INVESTIGATION

Virgil Sanders

Introduction

The following report is a summary of the experimental accomplishments made in Ring Laser Technology during the period September 1, 1969 - August 31, 1970. This work is an investigation to determine the effect on dual polarized ring laser systems of force field induced birefringence in intra-cavity media; as such, the investigations develop part of the technology required to understand the effect of fields (and ultimately gravitational fields) on the polarization of electromagnetic signals. The emphasis during this period was to make some quantitative stress measurements on a diametrically loaded fused silica disc which was an active part of the optical cavity of a dual polarized linear laser. The force field applied to the disc would split the degeneracy between the two states of optical polarization simultaneously excited within the cavity and would permit, after heterodyning, the detection of the beat between the two optical signals. This beat signal would be proportional to the field of force applied to the fused silica disc.

Summary

The experiments successfully determined an induced beat frequency between polarization states as a function of the diametrical load on a 0.3 x 1.0 inch fused silica disc. A typical measurement is displayed in Figure 1b. A change of

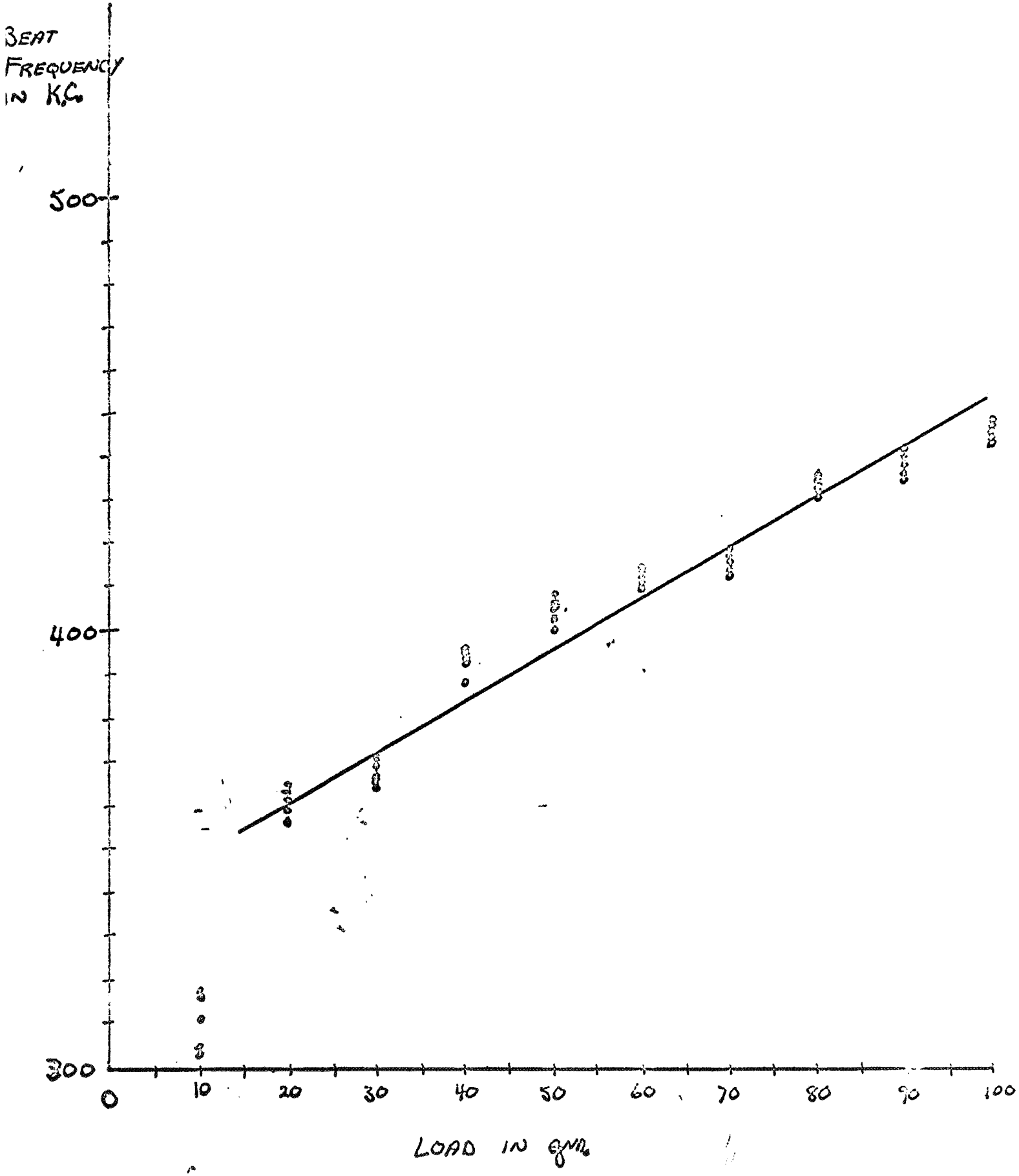

BEAT FREQUENCY IN K.C.
500
400
300
0
10
20
30
40
50
60
70
80
90
100
LOAD IN gm.

Figure 1b

ten grams load on the disc, in a gravitational field of one g, corresponds to change in index of refraction in the fused silica disc of $\Delta n \sim 10^{-8}$. The corresponding beat frequency was about 20 Kilohertz. Note that a change of the gravitational field by one part in a million would, for a load of 500 grams, give a beat signal change of one hertz—a fact which implies that such a device could be used as a gravimeter.

The Experiment

A diagram of the experimental apparatus is shown in Figure 2b. The apparatus as shown contains a He-Ne laser tube (supplied by Spectra Physics) capped at both ends of the discharge tube with anti-reflection coated windows. These windows are mounted perpendicular to the axis of the laser tube such that two mutually perpendicular states of polarization may be excited within the laser cavity at the same time. The fused silica substrate is a disc, one inch diameter by three tenths of an inch thick. The beat frequency detector consisted of a "Tropel" Model 330 light detector and a "Monsanto" Model 101 A counter-timer. The beat frequency is obtained by tuning the cavity such that without stress on the fused silica disc only one, polarization degenerate, longitudinal mode exists within the optical cavity; then a diametrical load is applied to the fused silica disc causing it to become slightly birefringent. The polarization

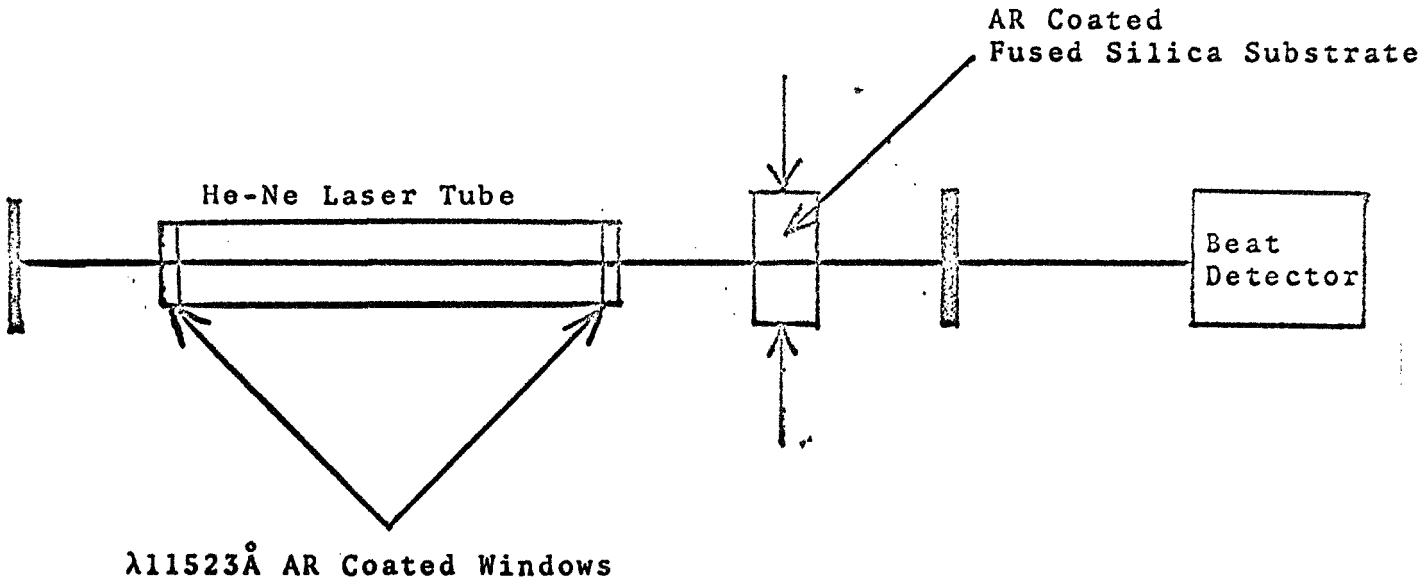

AR Coated
Fused Silica Substrate
He-Ne Laser Tube
Beat
Detector
λ11523Å AR Coated Windows

Figure 2b

degeneracy is lifted by the application of the stress induced birefringence such that the one longitudinal mode becomes non-degenerate. One portion of the mode is polarized in the direction of a principal stress axis, and the other portion of the mode, at a slightly different frequency, is polarized in the direction of the other principle stress axis. The two optical signals are heterodyned, and the resulting beat frequency is measured. The beat frequency, as shown in Figure 1b is, to first order, linearly related to the amount of induced birefringence. However, for the apparatus used above, in the vicinity of about 300 kilohertz the non-linear effects of the gas discharge induced birefringence. However, for the apparatus used above, in the vicinity of about 300 kilohertz the non-linear effects of the gas discharge induce a mode locking phenomena and quench the beat frequency. Therefore a certain amount of birefringence, as system offset, must be induced before the mode splitting can be detected.

Calculations using Brewster's stress-optics law were applied to a sample of fused-silica of the particular geometry used in this experiment. These calculations indicated that a change of ten grams diametrical load on the fused silica disc would change the index of refraction by one part in 10^{-8} at the center of the disc. This amount of change in index of refraction should change the beat frequency by about forty kilohertz. The graph in Figure 2 shows a change of less than

twenty kilohertz per ten grams. This discrepancy is attributed to small geometrical irregularities between the idealized calculation and the actual experiment.

This work was reported to the Texas Academy of Sciences on May, 1970 to March 5, 1970.

Following the detection of the beat signals between the polarization states in the linear laser cavity (as described above), the apparatus was reconstructed to form a triangular ring optical cavity. The small bore He-Ne gas discharge tubes prevented the excitation of the lasing action in the visible red region, and consequently further study of the polarization-propagation direction degeneracies was impossible in the visible spectrum. A linear (non re-entrant) system using the same numbers of reflecting surfaces and the same gas discharge tubes (hence containing the same loss factors) could be made to lase in the visible red portion of the spectrum, but experiments indicated a large loss in system gain due to a combination of limiting aperature (1 mm) and (effective) radius of curvature of the laser beam. It was determined that laser discharge tubes designed for Phase II work will require a somewhat larger (~2mm) bore diameter in order that the system gain will support lasing operation in the ring configuration).

Without the experience of operation in the visible region, an infra-red system was then constructed from existing components,

and (fortunately) lasing action was achieved at 1.15 micron. The triangular cavity (odd numbers of mirrors) permitted a geometrical splitting of the polarization states, while the re-entrant configuration permitted the detection of the beams propagating in different directions. A Tropel spectrum analyzer used in conjunction with a polarized plate permitted the detection of all four states of infra-red excitation. Quantitative measurements are in progress at the time of writing of this report; the qualitative results described above serve as the preliminary data to justify Phase II of the proposal: the experimental verification and utilization of the four-fold degeneracy of electromagnetic signals.

APPENDIX C A GENERAL RELATIVISTIC ANALYSIS OF THE ELECTROMAGNETIC PROPERTIES OF FIELDS

Ronald Borochoff

The subject of the proposed work is a study of the optical phenomena associated with various fields. In particular we will study the phenomena associated with gravitational, electric and magnetic fields. By including the possibility that the fields may be in motion or that they may exist in the presence of material media, we hope to gain a better understanding of such phenomena as the Lense-Thirring effect and the Kerr and Faraday effects. Ultimately we hope to gain a better understanding of the coupling of these fields with the polarization properties of electromagnetic signals.

The basic idea is to exploit the notion hinted by E. J. Post that fields can be considered to be optical media. This idea is presented principly in his book Formal Structure of Electromagnetics.

Post's work is based mainly on the fact that Maxwell's equations, stated in terms of the four well known field vectors (E, D, B & H), are entirely independent of material. Reference to material properties is given only in the constitutive equations relating the field vectors through the electric and magnetic permeability matrices:

1)
$$\overline{D} = [e]\,\overline{E} - [\gamma]\,\overline{B}$$
$$\overline{H} = [\mu]^{-1}\overline{B} + [\gamma]\,\overline{E}$$

Equivalently, when stated in tensor form, Maxwell's equations are also independent of the Riemannian metric. Post has shown that the metric enters into electromagnetism at the same point and in the same fashion as material media. A set of constitutive equations are defined involving the metric, they are given by:

2) $$H^{\mu\nu} = 1/2\ \underset{o}{\chi}^{\mu\nu\alpha\beta}\ F_{\alpha\beta}$$

where

3) $$\underset{o}{\chi}^{\mu\nu\alpha\beta} = \sqrt{-g}(g^{\mu\alpha}g^{\nu\beta}-g^{\mu\beta}g^{\nu\alpha})$$

and where $H^{\mu\nu}$ contains $\overline{D}$ and $\overline{H}$ and $F_{\alpha\beta}$ contains $\overline{E}$ and $\overline{B}$; $\chi^{\mu\nu\alpha\beta}$ is called the metric-dependent constitutive tensor. This particular tensor is obtained entirely from mathematical considerations. A second tensor, the material constitutive tensor, denoted $\underset{m}{\chi}^{\mu\nu\alpha\beta}$, can be obtained for any material in the system. It is obtained from experimental observation. The final constitutive tensor is hypothesized to be a sum of these two:

$$\chi^{\mu\nu\alpha\beta} = \underset{o}{\chi}^{\mu\nu\alpha\beta} + \underset{m}{\chi}^{\mu\nu\alpha\beta}$$

It is at this point that field and space properties begin to play a role equivalent to that of material media. Equations 2) and 3) give a tie-up of constitutive properties with metric properties.

To facilitate study, it is possible to map the constitutive tensor onto a 6 dimensional space and obtain a matrix relation for the fields; thus equation 2) becomes:

$$4)\ . \qquad \begin{pmatrix} -\bar{D} \\ \hline \bar{H} \end{pmatrix} = \left[\begin{array}{c|c} \varepsilon & \gamma \\ \hline \tilde{\gamma} & \mu^{-1} \end{array}\right] \begin{pmatrix} \bar{E} \\ \hline \bar{B} \end{pmatrix}$$

The dotted partitions denote the 3-D submatrices and vectors. The permeability submatrices function the same in 3-D whether they come from the metric or from material.

This general approach has been used successfully by Post and his colleagues to analyze such optical phenomena, in a flat space, as the Sagnac effect and the Fresnel-Fizeau effect. He has also shown the possibility of properly representing such polarization rotation phenomena as the Faraday effect and natural optical activity.

Most of the work done in this area, so far, has been on phenomena occurring in a flat space. In this particular case the metric constitutive tensor is simply obtained and easily interpreted; i.e., it is formed from products of the Jacobian elements.

However, in general, the metric corresponds to that of a curved space and is obtained as a solution to Einstein's equation.

Of especial interest are those metric solutions to the combined Maxwell-Einstein equations:

5) $$R_{\mu\nu} = \lambda T_{\mu\nu}$$

where

$$T_{\mu\nu} = F_{\mu\alpha} F^{\alpha}{}_{\nu} + 1/4\, g_{\mu\nu} F_{\alpha\beta} F^{\alpha\beta}$$

is the Maxwell energy-momentum tensor.

The geometry of these metrics has been studied in the past by such workers as G. Y. Rainich, J. A. Wheeler, and C. W. Misner.

Various simple solutions to these equations have been obtained; among them are the spherically symmetric solution of Nordstrom, the axially symmetric solutions of H. Weyl, and certain stationery solutions corresponding to crossed $\overline{E}$ and $\overline{B}$ fields studied by B. K. Datta and A. K. Raychaudhuri.

It is planned that a formalism be developed for the study of optical phenomena associated with these fields. This formalism will be based on a study of the symmetry properties of the constitutive tensors and metrics associated with the fields. This approach, in the final analysis, should be parallel to that used in studying the optical properties of crystals and various non-isotropic, inhomogeneous media. Thus, a general "covering theory" would ultimately be developed, applicable to all optical phenomena whether classical or general relativistic in origin.

While it might be pointed out that, in principle, most of the intended results can be obtained directly from the Einstein equation, in practice this is not such a simple task. The present approach has the advantage of giving simple intuitive meaning to the various metric elements. Using the metric solutions directly, it is not at all obvious in what way metric and matter should be treated when together in these systems. Further, by treating the metric as a material media, optical phenomena corresponding to fields in motion can be more easily studied and interpreted. It is thus planned that polarization rotation associated with rotating fields can be studied further. An effect of this type has already been predicted independently by N. L. Balazs and by G. V. Skrotskii for a rotating spherical mass.

The main obstacle to the present work is not necessarily obtaining solutions to the Maxwell-Einstein equations, but being able to give the proper physical interpretation to the already existing solutions. Two very basic problems exist for those attempting to apply the formalism of general relativity to physical prediction and observation:

(1) The equivalence problem: there is no simple test available for showing whether or not two metric fields are equivalent; i.e., given two apparently different metric fields, there is no simple way to show whether or not they correspond to the same physical situation, but differ only in their coordinate representation.

(2) The problem of physical interpretation or observation: there is no simple way (at least in a non-flat space) to separate out those effects which belong intrinsically to the fields from those which belong simply to the coordinates; i.e., coordinate forces and other effects are seldom as obvious as centrifugal and Coriolis forces are in the polar coordinates of flat space. Thus, the ability to predict what might be observed in nature is severely hampered.

In a flat space, these problems are easily handled, enough Galilean and Lorentzian invariants exist such that the equivalence of systems can be analyzed. Coordinate type effects are always separable since they always appear as Jacobian transformation coefficients from a Euclidean space.

The only non-flat spaces which are tractable are those which are asymptotically flat; e.g., the Schwartzschield and Nordstrom solutions. This is one reason why the only physical results that have been obtained from general relativity have come from the Schwartzschield solution.

The reason why this problem arises in this study is that it blocks the attempt to study directly the constitutive tensor symmetries corresponding to uniform, constant electric fields. The metric corresponding to these fields is axially symmetric and is not asymptotically flat. Other systems studied find corresponding difficulties.

What is needed, then, is an invariant representation for these solutions. One that will give numerical results which are truly independent of the coordinate system chosen. A number of attempts have been made by various workers to solve this problem, among them I might mention the intrinsic coordinate system of P. Bergmann and the harmonic coordinates of V. Fock. However, the most promising formulation seems to be that given by A. Z. Petrov.

In this method, Petrov has developed a way to map the four index curvature tensor onto a matrix display (in the way we have done with the constitutive tensor) and then to reduce this matrix, simultaneously with the metric, to a canonical form. In the process he obtains the invariants, eigenvalues if you will, of the curvature tensor. This canonical form, and the eigenvalues are, of course, independent of the original coordinate system. The method turns out to be applicable to a curvature tensor corresponding to any type of Riemannian space whether or not the stress-energy tensor vanishes. Petrov has hereby been able to classify the curvature tensor into three possible types, depending on the form of the Segre' characteristic of the matrix. Along with a similar classification of the stress-energy tensor, also into three types, he has shown there are only nine possible energy states of the gravitational field in general relativity.

However, little has been done to examine sub-classifications of these space types. This is one aspect which will be pursued in the study of symmetries associated with the various metrics. What will be obtained as a by-product, is a sub-classification of spaces according to optical properties. This work was reported to the Texas Academy of Sciences on March 5, 1970.

APPENDIX D STATEMENT OF WORK: PHASE II (9/1/70 - 8/31/71) NGR-44-005-085

During Phase II, the work on the Cotton-Mouten effect, initiated in Phase I, will be completed. In addition, the potential of the apparatus developed during Phase I to act as a flyable gravimeter will be more thoroughly investigated.

The major experimental objective of Phase II will be the construction of an apparatus to detect quadrature beat signals between the four-fold states of electromagnetic wave propagation. These states are of course degenerate in an inertial frame, and the effect of a gravitational or other force field is to split the degeneracies. The four states of propagation are the two states of polarization and the two states of propagation direction. The development of an apparatus to measure and study these four states of propagation, and the utilization of such an apparatus in the presence of force fields which will split the degeneracies and produce beats between the states will be undertaken in Phase II. This work is based upon the foundation established in Phase I that such states can be experimentally established in an appropriately constructed ring laser system.

Theoretical efforts will be continued to further the understanding of gravitational fields on elyctromagnetic polarization. In particular a numerical estimate of the effects of a large rotating stellar mass on electromagnetic

polarization will be made, along with an analysis of the previous experiments conducted in Phase I.

This work will be under the supervision of Dr. Robert M. Kiehn at the University of Houston,

Proposed Budget: Phase II (9/1/70 - 8/31/71) NGR-44-005-085

	U of H	NASA	Total
A. Salaries			
Dr. R. M. Kiehn (1/9 time + 2-1/2 mo. summer)	$ 2,250	$ 5,625	$ 7,875
Graduate Student Stipend @ $300/month		3,600	3,600
Secretary (part time)		750	750
Total Salaries	$ 2,250	$ 9,975	$12,225
B. Capital Equipment			
Lasers & Optics		7,000	7,000
Electronics		2,000	2,000
C. Expendable Equipment & Supplies			
Mech/Electronic Parts		500	500
Mech/Tech Services & repairs		250	250
D. Publication Costs		500	500
E. Travel (Domestic)		500	500
F. Employee Benefits		261	261
Total	$ 2,250	$20,986	$23,236
Indirect Costs (44.44% Item A)	999*	4,433	5,432
TOTAL PROJECT COSTS	$ 3,249	$25,419	$28,668

*Computed figure: No memorandum account will be maintained.