U.S. DEPARTMENT OF COMMERCE
National Technical Information Service

AD-A025 669

COHERENT OPTICAL ADAPTIVE TECHNIQUES (COAT)

ROCKWELL INTERNATIONAL CORPORATION

PREPARED FOR
ROME AIR DEVELOPMENT CENTER

16 OCTOBER 1972

174096

RADC-TR-72-341
Technical Report
16 October 1972

COHERENT OPTICAL ADAPTIVE TECHNIQUES (COAT)

North American Rockwell, Electronic Gp.
Research & Technology Division

Sponsored by
Defense Advanced Research Projects Agency
ARPA Order No. 1279, Amendment 5

Approved for public release;
distribution unlimited.

Rome Air Development Center
Air Force Systems Command
Griffiss Air Force Base, New York

COHERENT OPTICAL ADAPTIVE TECHNIQUES (COAT)

C. L. Hayes

Contractor: North American Rockwell, Electronic Gp.
Research & Technology Division
Contract Number: F30602-72-C-0417
Effective Date of Contract: 20 March 1972
Contract Expiration Date: 20 January 1973
Amount of Contract: $213,500.00
Program Code Number: 2E20

Principal Investigator: C. L. Hayes
Phone: 714 632-2239

Project Engineer: Robert F. Ogrodnik
Phone: 315 330-2747

This research was supported by the Defense Advanced Research Projects Agency of the Department of Defense and was monitored by Robert F. Ogrodnik, RADC (OCTM-1), GAFB, NY 13441 under Contract F30602-72-C-0417.

PUBLICATION REVIEW

This technical report has been reviewed and is approved

Robert F. Ogrodnik

RADC Project Engineer

FOREWORD

This Quarterly Technical Report is submitted to the Rome Air Development Center in partial fulfillment of the requirements of Contract F30602-72-C-0417, "Coherent Optical Adaptive Techniques". The program was initiated on 20 March 1972.

The work described in this report was performed by the Lasers and Advanced Radiation Systems Group, Research and Technology Division, Electronics Group of North American Rockwell, 3370 Miraloma Avenue, Anaheim, California 92803.

Major contributors to this effort are:

Principal Investigator: C. L. Hayes

Contributors: R. A. Brandewie
W. C. Davis
G. E. Meyers
J. F. SooHoo
J. N. Yamamoto

TABLE OF CONTENTS

I. INTRODUCTION

The first quarterly progress report for this program described in detail the design of the optical and electronic systems required for performance testing of the COAT (Coherent Optical Adaptive Techniques) concept. This report is directed towards the results of component tests and initial system operational data. Before presenting these data, however, a brief statement of the program goals and test procedures is appropriate.

Propagation of coherent radiation through the atmosphere is significantly affected by meterological phenomena and turbulence conditions. Induced wavefront distortion limits the ability of a system to bring such radiation to a focus as may be required in future systems. The COAT contract is a program directed towards the design, construction, and experimental demonstration of a multi-aperture optical system which can effectively compensate for such atmospherically induced aberrations. Employing the phase conjugation principle for wavefront control, a six-element linear array is being fabricated for operation at a wavelength of 10.6 μmeters. Detailed tests will be conducted to evaluate performance with respect to the following primary objectives:

1. Compensate for atmosphere propagation effects at 10.6 μmeters and provide improved focusing capability at the target;

2. In a multiglint target scenario, establish the ability of system to lock onto a single glint point;

3. Acquire and track a glint point which moves across the array field of view.

The last task indicates that correction for atmospheric effects is not the only benefit to be derived from the COAT system. The ability to provide automatic pointing and tracking is inherent to the system and within the diffraction limit of an array element, the system will acquire and track a target.

To evaluate the performance of this system, tests will be conducted over two ranges --- 1 km and 10 km. These ranges correspond to near field and far field operation of the array. Full meterological instrumentation is provided to characterize atmospheric parameters and data will be taken in both the adapted and unadapted modes for comparison with analytical results derived from computer simulation.

II. SUMMARY

Propagation of coherent radiation through the atmosphere is significantly affected by meterological phenomena and turbulence conditions. Thermal "blooming" of high energy beams is also known to present propagation problems. That is, induced wavefront distortion limits the ability of a system to bring such radiation to an optimum focus as may be required for some applications. Theoretical calculations show that the ability of a fixed focus system to concentrate energy does not improve with increasing aperture size as classical theory predicts due to these effects. Previous contractual efforts --- both theoretical and experimental ---have shown that coherent optical adaptive techniques (COAT) can be used to compensate for these propagation difficulties. The wavefront correction required is accomplished through the use of phase controlled multi-aperture arrays to correct the distortion --- naturally occurring or induced. In addition, other benefits are derived from segmenting the aperture in that smaller, less expensive optical components can be used with an associated relaxation in pointing requirements, mounting and pointing hardware.

The first quarterly report furnished in detail the design which, when implemented, can accomplish the compensation task and provide focusing at the target. Table II-1 lists some of the pertinent design parameters. This report presents some of the results of component evaluation tests for devices to be used in the system.

TABLE II-1

CONDENSED TABLE OF COAT PARAMETERS

OPTICS	
Number of Apertures	6
Power per Channel	0.3 watts
Size of Apertures	2.5 cm
Array Geometry	Linear (1 x 6) Variable Width (Nominally 3 cm)
Scatter Suppression	Polarization Discrimination Transmitter - Vertical Receiver - Horizontal
Optical Material for Lenses and Beamsplitters	NaCl
Phase Modulator	Acousto-Optic Bragg Cell Center Frequency - 18 MHz
Quarter Wave Plates	$5/4\lambda$ Cadmium Sulfide
LASER	
$10.6 \mu m$ CO_2 - Single Mode	60 watts (max)
DETECTORS	
PbSnTe ($77^{o}K$)	Heterodyne Mode Receiver
ELECTRONICS	
Post Detection Amplifier	Current Mode Operation
Processing I-F	4.5 MHz
Servo Control	Phase Lock
Phase Detector Range	$\pm 2\pi$ radians
Tracking & Acquisition Bandwidth For a Transit Time of $7.0 \mu s$	50 KHz

Section III includes the test results for the frequency modulator, detector, laser and electronics subsystems. The key element, frequency modulator, has been thoroughly tested with performance meeting theoretically defined specifications. Fabrication of these devices has been delayed due to the inability of a vendor to provide the required material (properly oriented germanium crystals). However, recent delivery of sufficient Ge boules to complete fabrication assures total system implementation. PbSnTe detectors are now being used for heterodyne receivers and have replaced Ge:Cu devices with their attendant requirement for liquid helium.

Initial system test results are given in Section IV along with a system modification which has been made. Performance is close to predicted values and signal-to-noise evaluation for the 1 km range indicates that plenty of margin for operation at a range of 10 km is present.

Using a previously developed computer simulation routine, a theoretical evaluation of how the array should perform has been completed. These results are presented in Section V and show the automatic acquisition capability of the system as well as the concentration of power on the target.

With the completion of frequency modulator fabrication, system tests of the array will be started and the power buildup on target will be measured at the target for comparison with computed values.

III. COMPONENT EVALUATION

A. ACOUSTO-OPTIC FREQUENCY MODULATOR

The key element in the adaptive system to compensate for wavefront aberrations is the frequency modulator which functions as a phase correcting device. Details of design are given in the first quarterly report and are only briefly presented here.

It is well known that Bragg scattering of light and sound in a crystal that is transparent to both can be utilized to shift the frequency of the light. The scattering is a maximum when the laser beam is incident upon the acoustic wavefront at the Bragg angle. The scattered laser beam is separated from the incident laser beam by twice the Bragg angle and is Doppler-shifted in frequency by an amount equal to the frequency of the traveling acoustic wave. By controlling the acoustic frequency in an appropriate manner, the light is then frequency modulated. Since frequency modulation is tantamount to phase modulation, the necessary phase correction capability is available with this approach.

The modulator is essentially composed of a germanium substrate with a $LiNbO_3$ transducer bonded to one end of the substrate and with an acoustic absorber attached to the other end (see Figure III-1). Since germanium is transparent to the CO_2 laser only if the crystal temperature is not too far above room temperature, a simple but effective cooling system has been constructed for maintaining the crystal below room tempera-

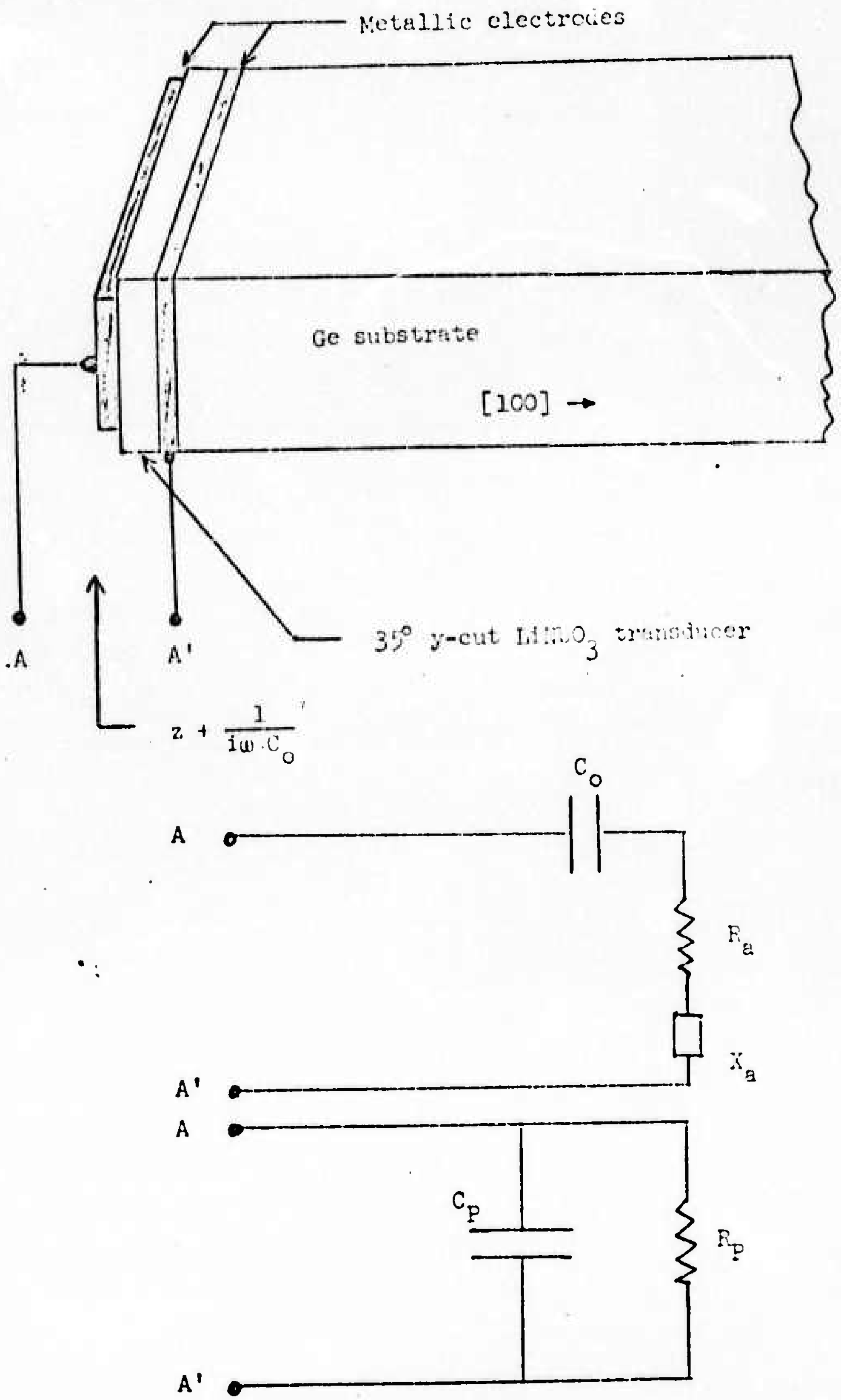


Figure III-1. Equivalent Electrical Circuits of Modulator at Transducer Terminals ture during operation. In general, the modulator is simple to operate and effective even for a relatively high-powered laser having a large beam diameter (~ 1 cm). Figure III-2 is an assembly drawing illustrating the adjustable mount along with the cooling apparatus.

With the acoustic propagation in the [100] direction of the germanium crystal, and the incident laser beam at Bragg angle to the acoustic wavefront, we have experimentally obtained a conversion efficiency of about 40% with 15 watts of electrical power applied to the $LiNbO_3$ transducer. The conversion efficiency is defined as the ratio of optical power in the deflected beam to that in the incident beam. In accordance with the theoretical prediction for this particular direction of acoustic propagation, the observed conversion efficiency is nearly independent of the incident laser polarization direction. It should be pointed out that a conversion efficiency of 40% can also be obtained with only about 5 watts of electrical power, providing that both the acoustic propagation and the laser polarization directions are confined to the [111] direction of the germanium crystal. A disadvantage of the [111] configuration is that the conversion efficiency decreases very rapidly as the polarization direction deviates from the [111] direction. For our applications it is required that the conversion efficiency should not be very sensitive to the direction of the laser polarization, and therefore we have confined our effort to the case in which the acoustic propagation is in the [100] direction of the germanium substrate.

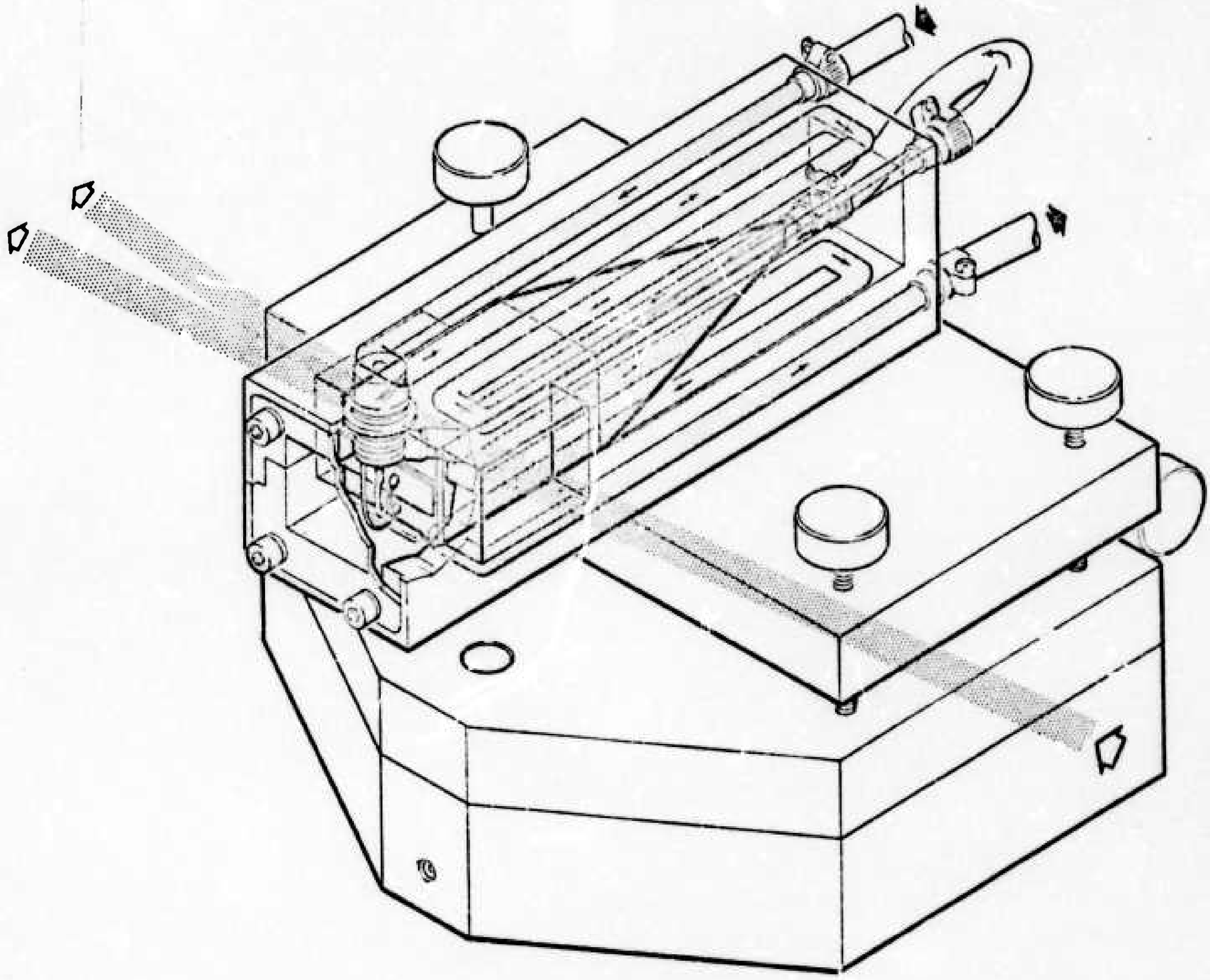


Figure III-2. Illustration of the Acousto-Optical Modulator

In order to achieve high conversion efficiency, relatively large amounts of electrical power must be coupled into the transducer. The R-F generator-network combination of Figure III-3 is used for coupling purposes to deliver power to the transducer as represented by the equivalent circuit of Figure III-1. The values of R_p and C_p for a typical transducer are as shown in Figure III-4. With this configuration a power level of 35 watts at 18 MHz can be applied.

Experimental testing to date has verified the validity of design. The conversion efficiency as a function of acoustic power has been determined from the measured optical and electrical powers. Figure III-5 illustrates the test results and indicates that the device performance is satisfactory for the particular application being considered.

The packaged device tested and to be used in the system is shown in Figure III-6. Included is the R-F power stage and VCO unit which is situated on top of the cooling jacket and positioning mount.

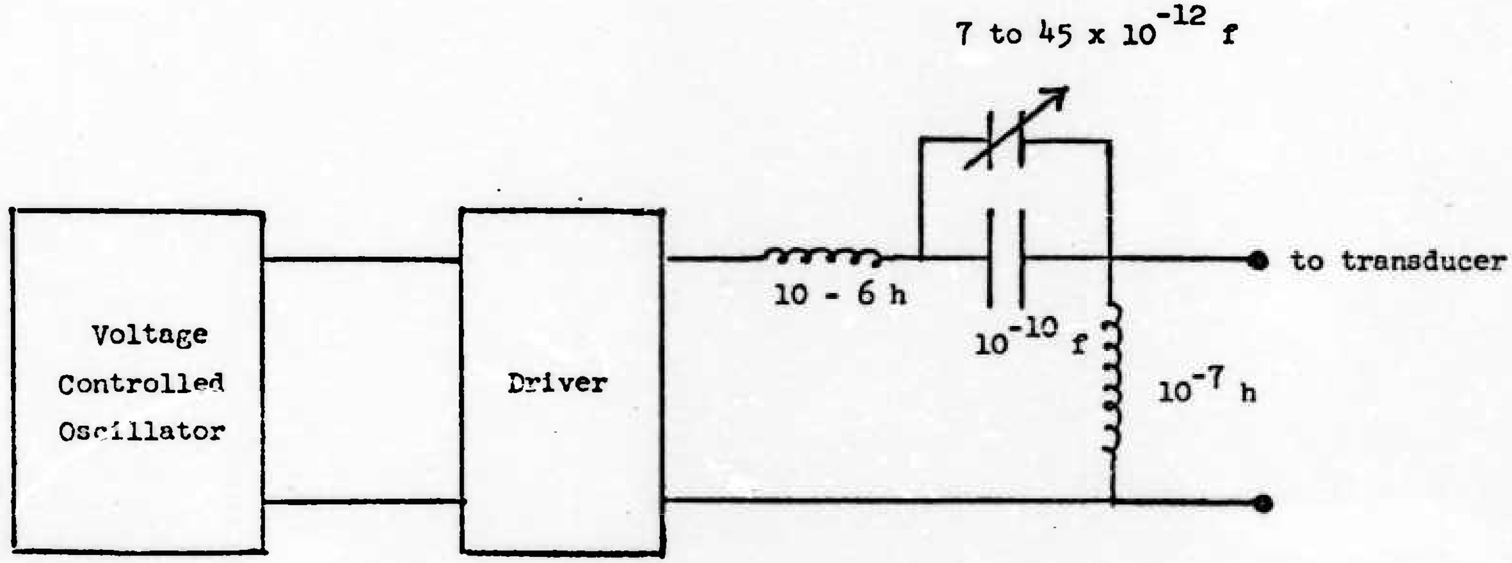


Figure III-3. Driving Network for Transducer Excitation

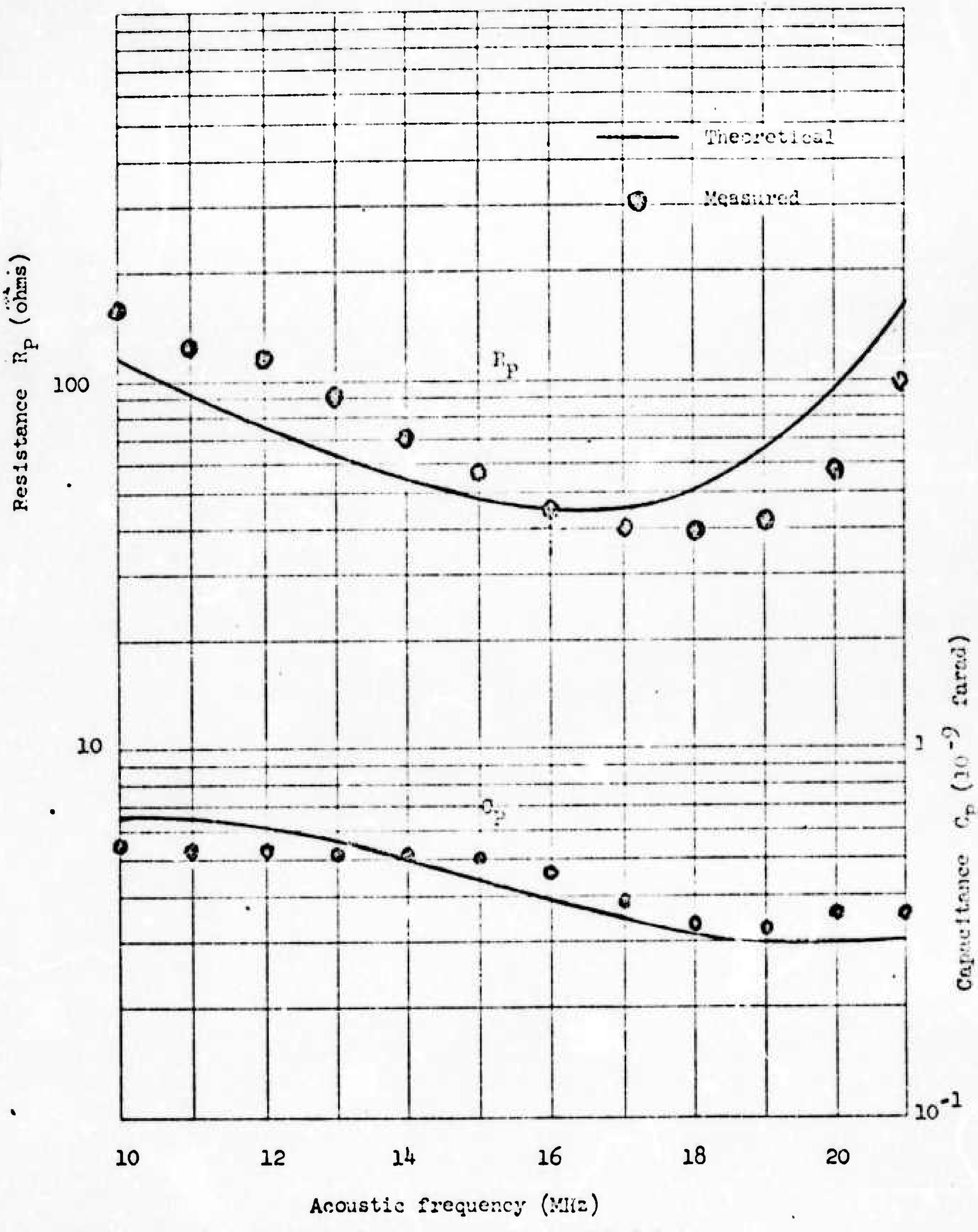


Figure III-4. Electrical Characteristics of Modulator VS Acoustic Frequency

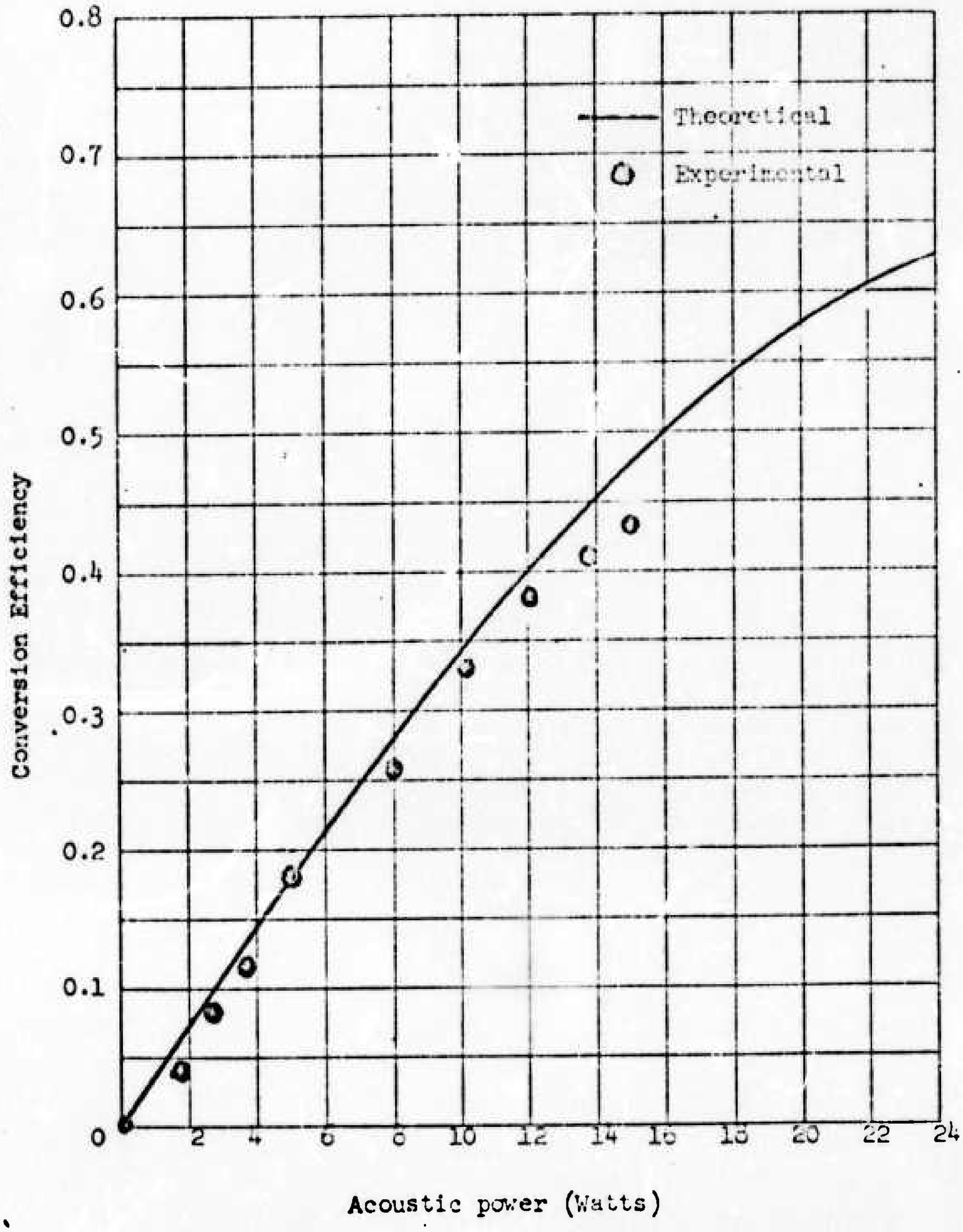


Figure III-5. Conversion Efficiency VS Acoustic Frequency

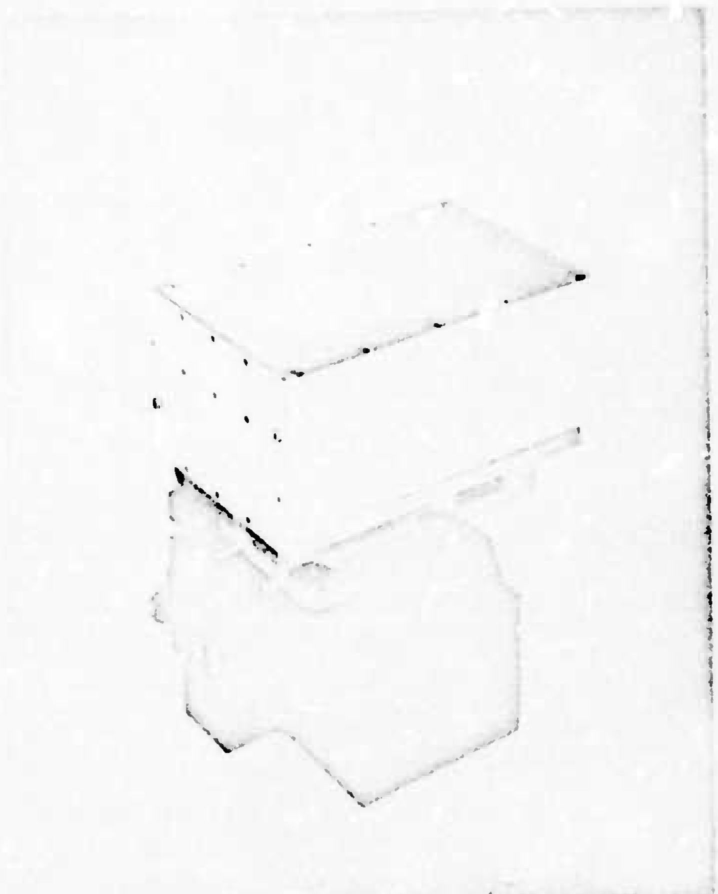


Figure III-6. Acousto-Optic Frequency Modulator for COAT System

B. DETECTORS

The COAT configuration presently being employed utilizes a heterodyne receiver in each channel (array element) as part of the processing to determine the relative phase between each channel. As originally conceived, Ge:Cu detectors were to be used in this capacity. However, since that time the North American Rockwell Science Center has been able to furnish PbSnTe detectors for use on this program. There are several distinct advantages to be gained through use of these devices. First, the requirement for operation at liquid He temperature ($4^{\circ}K$) is relaxed to operation at liquid N_2 temperature ($77^{\circ}K$) and the inherent advantage from a cryogenic standpoint is obvious. Second, the photovoltaic mode of operation yields a 3 db improvement in the quantum-limited signal-to-noise ratio when compared to the photoconductive Ge:Cu material. Third, the post-detection preamplifier can now be operated in the current mode to obtain an improvement in frequency response through proper impedance matching techniques. Thus, from a system standpoint, these devices are very desirable and will be used on this program.

The six detectors to be used in this effort have been mounted in dewars as shown in Figure III-7. The optical system has been designed to permit the placement of two detectors in each of three dewars. Tests have been run to evaluate frequency response of these devices when coupled with a current mode amplifier and are given in Figure III-8. Two different

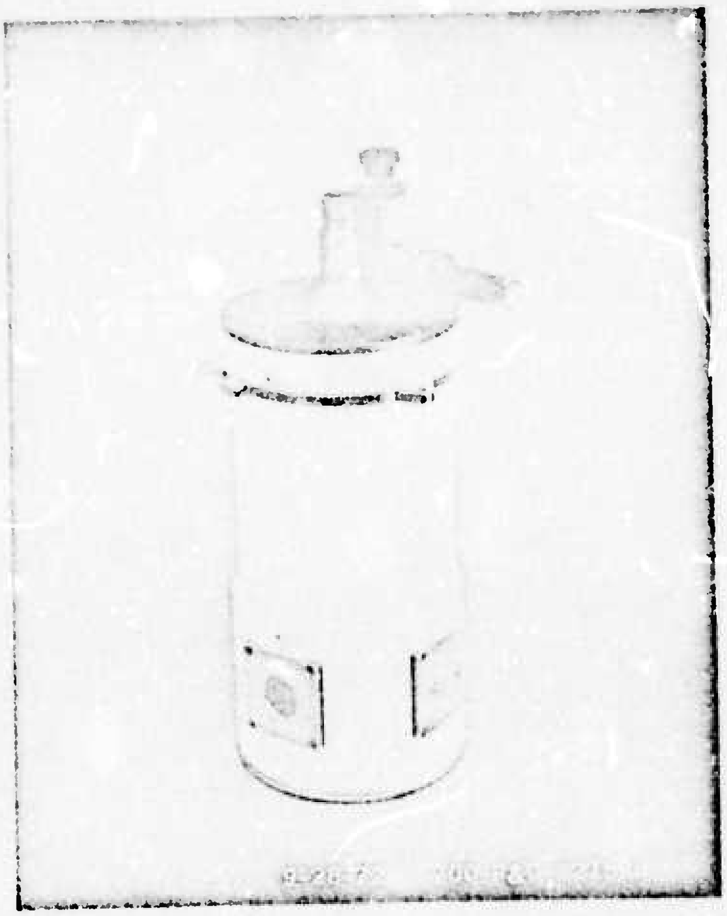


Figure III-7. Dewar for Use with PbSnTe Detectors (Two Devices Per Dewar)

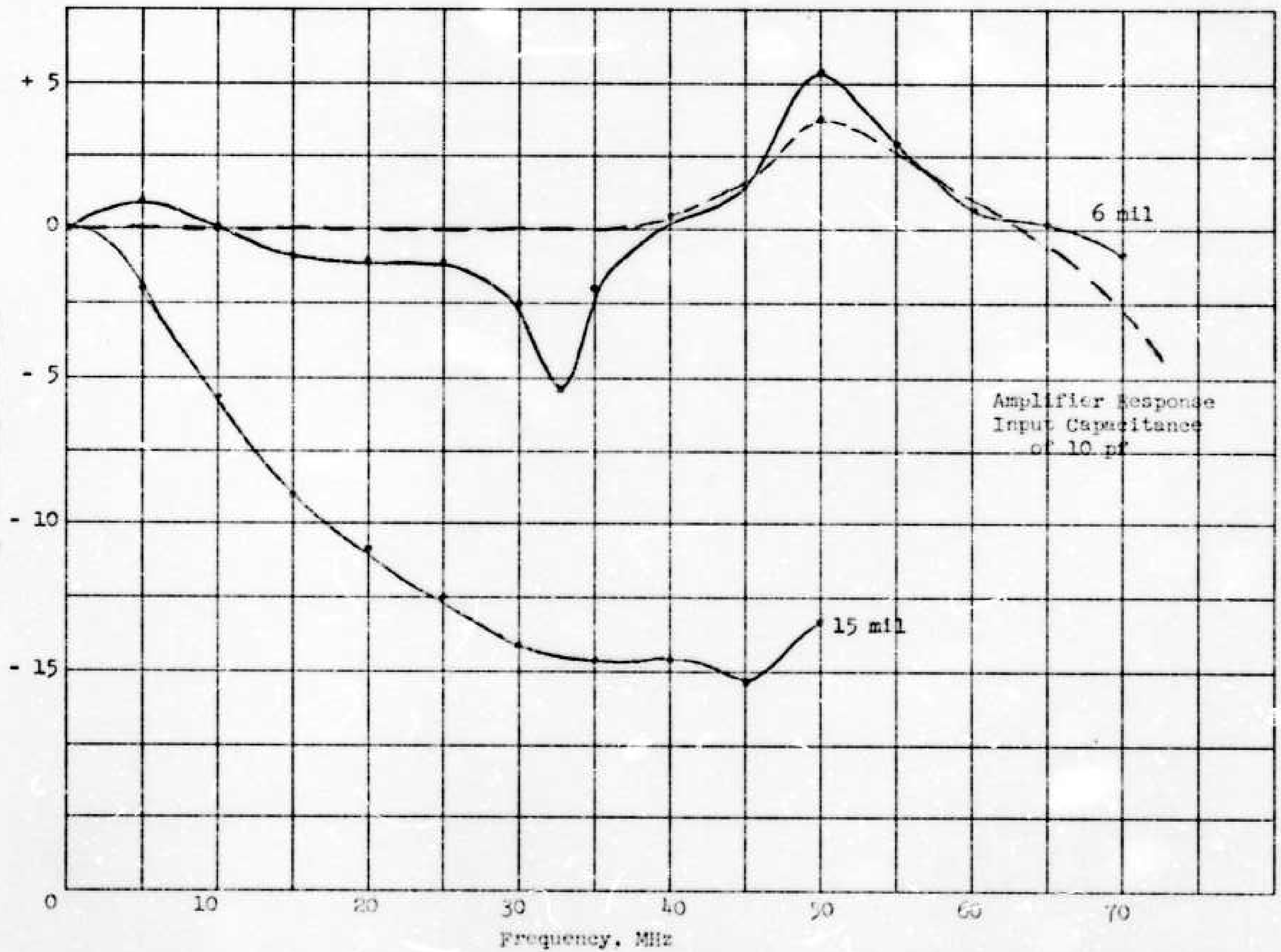


Figure III-8. PbSnTe Frequency Response (10.6 μm) types of detectors of different dimensions (6 and 15 mil diameters) were tested. The tests were performed using an amplifier having a bandwidth of 10 MHz and an electro-optic modulator to amplitude modulate a 10.6 μm laser. The relative response curves indicate successful operation is to be expected over a large bandwidth.

To facilitate the use of the larger device, a system change has been introduced to take advantage of the better response in the lower frequency range. Several other benefits accrue from this approach and will be described in detail in Section IV.

C. ELECTRONICS

As described in detail in the first quarterly report, the COAT system can be characterized as a multiple channel heterodyne transceiver employing common transmit/receive optics for each channel. Adaptive compensation is achieved through electronic processing of the received signals within a closed loop to generate a transmitted wavefront which is the conjugate of the received wave. At the same time, isolation from noise sources and phase perturbations must be provided. For reference, the simplified configuration of Figure III-9 which accomplishes these tasks is presented. The detector, i-f amplifier, phase detector, voltage controlled oscillator, and frequency modulator provide the closed loop servo control. This is done by sampling the relative phase difference between each channel and a reference and using this signal to control the frequency modulator through the voltage controlled oscillator which then provides automatic compensation of the transmitted wave.

Each function of the loop has been designed, fabricated and tested. The post-detection preamplifier operates in the current mode to provide a virtual ground to the detector. A bandwidth of 70 MHz has been designed into this unit to facilitate testing procedures. In operation, the bandwidth is limited by the i-f amplifier to approximately 200 KHz.

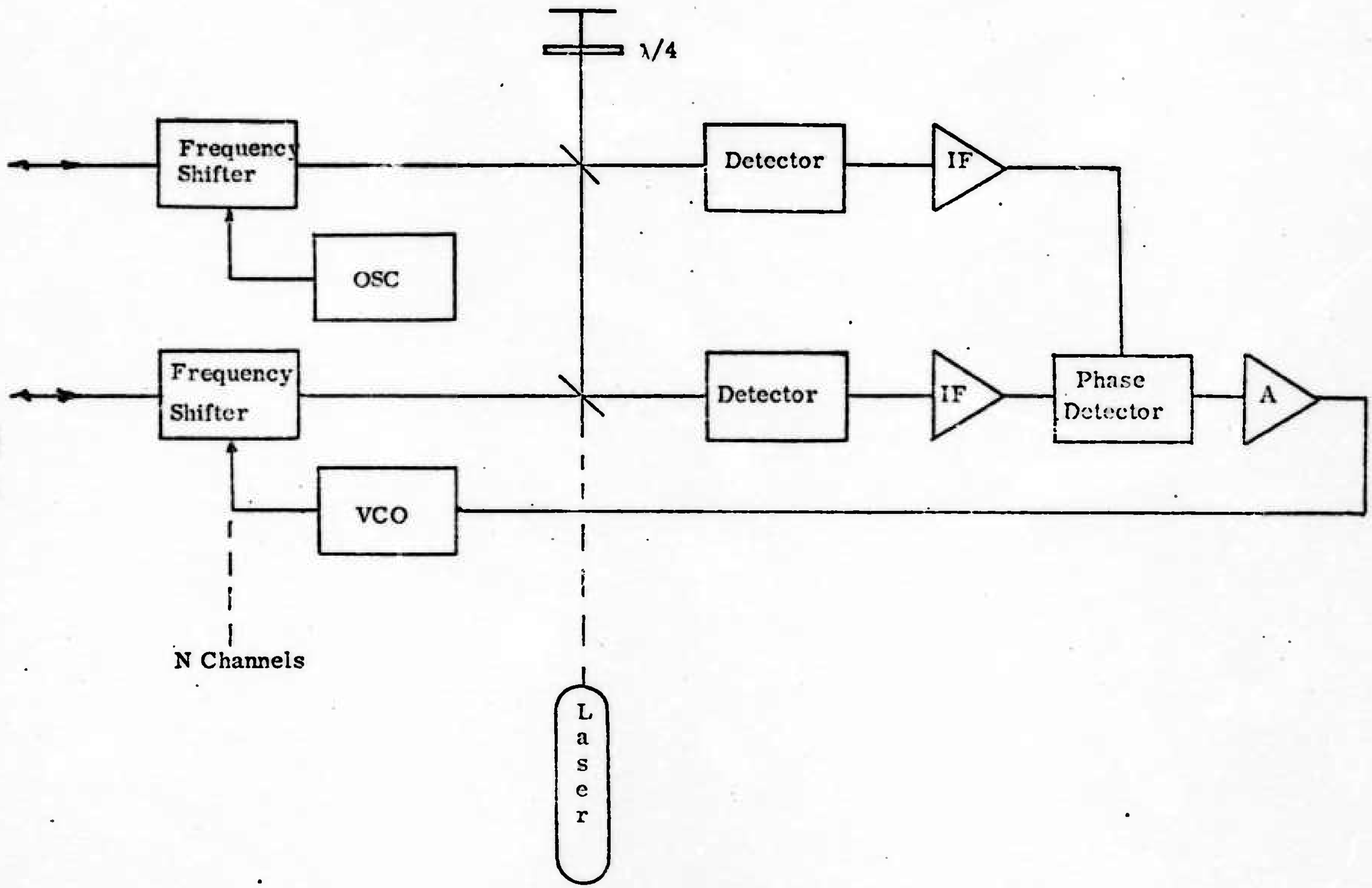


Figure III-9. Simplified Operational Diagram for N Element, COAT

The phase detector which has been mechanized has the characteristics shown in Figure III-10. The sensitivity (slope) has been set at 1 mv/degree. When coupled with the VCO which has a frequency sensitivity set at 1 KHz/mv, the overall tracking sensitivity is 1 KHz per degree of phase error. This gain parameter has been set to this value initially, but can readily be changed to provide optimum operation if required. When operated in the frequency tracking mode, this system can track to $\pm$ 360 KHz with no ambiguity and should provide adequate acquisition margin for a moving target.

The r-f power to drive the acousto-optic Bragg cell is furnished by a power amplifier driven by the voltage controlled oscillator. Typically, up to 25 watts of power can be delivered to this device and good conversion efficiency (40%) obtained.

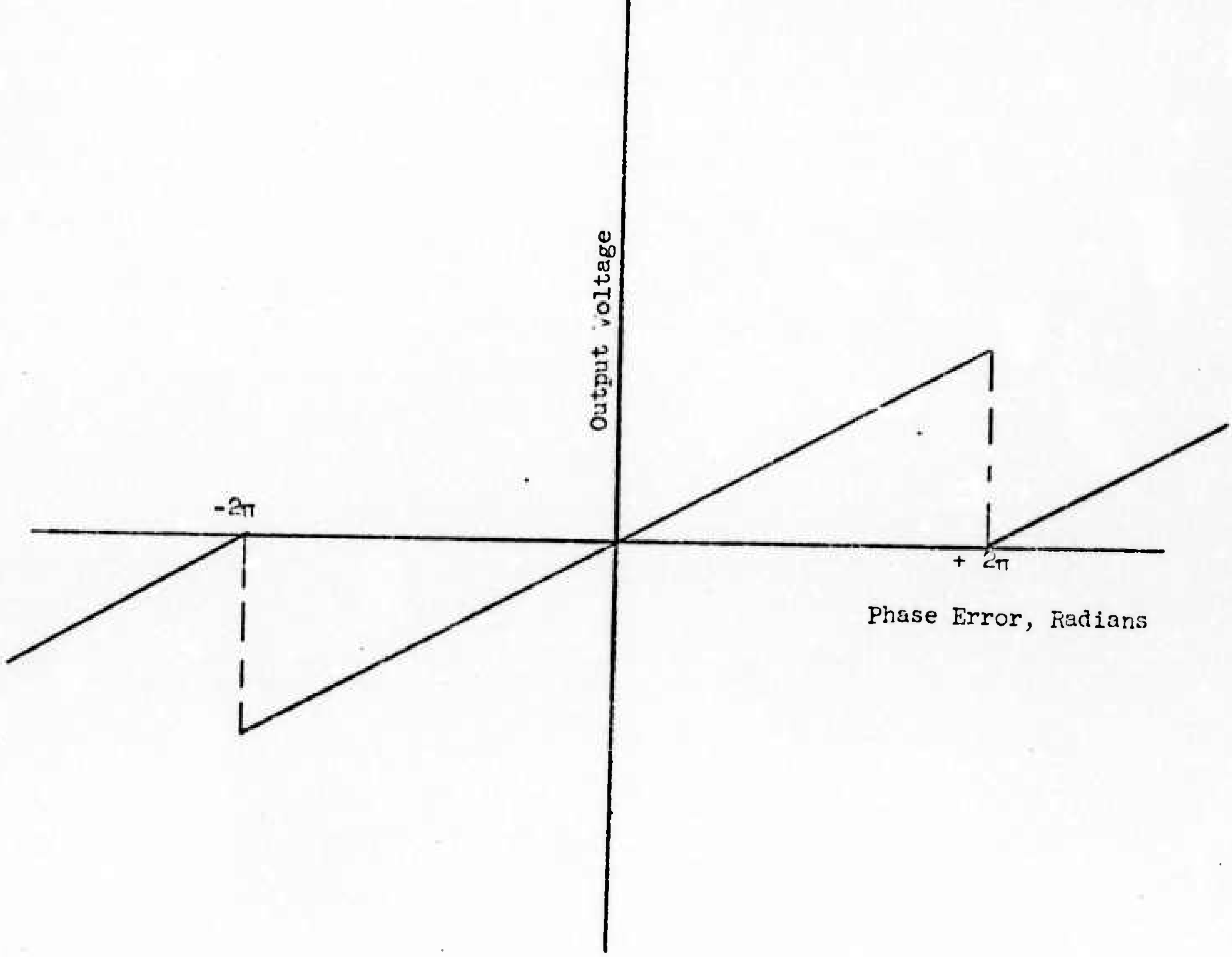


Figure III-10. Phase Detector Characteristics

D. LASER

The COAT laser has been assembled and tests have been completed to assure that adequate power and stability will be provided for system operation. The basic construction consists of two plasma tubes in a folded configuration to obtain the desired output power in a reasonable space (Figure III-11). Each tube has a bore of 1.1 cm and a gain length of 1.54 m. The cavity length is 3.5 m which yields a Fresnel number of 0.864. The TEM_{00} polarization direction is defined by means of four intracavity Brewster windows of sodium chloride. These windows are mechanically aligned with the table surface and provide the reference polarization for the COAT optical system.

In order to minimize amplitude fluctuations in the output beam the entire laser structure has been enclosed in a plexiglass shield. This shield isolates the intracavity spaces from room air currents which introduce significant amplitude fluctuations. Also isolated are acoustic coupled perturbations from the room environment. In addition, the enclosure serves as a dust shield and reduces maintenance requirements on the laser optics.

Performance tests have yielded a TEM_{00} measured output of 60 watts in the P(20) transition. Amplitude stability was measured with a wide bandwidth PbSnTe detector and a variation of less than 1% was recorded and is well within the acceptable limits.

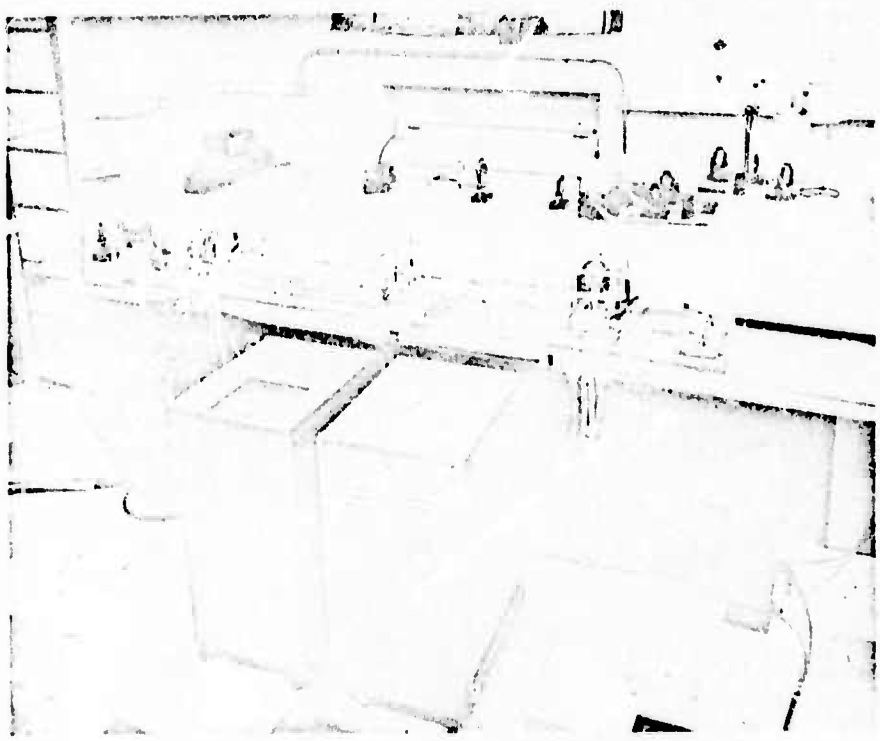


Figure III-11. CO_2 Laser for COAT System

The self-compensating interferometer being used to implement the optical assembly directs a portion of the output energy back towards the laser cavity. Without adequate isolation, the laser would exhibit instabilities since an attempt would be made to lock onto this injected signal. However, this instability occurs only after a 400 mw threshold is met (the return polarization is orthogonal to the exiting polarization). Making use of a Ge Brewster window in the beam path to discriminate and reject the orthogonal polarization, interaction effects of this nature have been completely eliminated.

IV. SYSTEM EVALUATION

A. SYSTEM MODIFICATION

One channel of the array has been constructed for performance evaluation as shown in Figure IV-1. Of interest in these preliminary tests was the overall system sensitivity to signals received from the one kilometer site. Measurements of signal-to-noise ratio, RFI, effects of detector responsivity, modulator conversion efficiency, scatter suppression, and quarter wave plate integrity were made. As a result of these tests, a system modification has been made as shown by Figure IV-2.

Several advantages are gained from this configuration without changing the phase conjugation principle of the system. The only change which is made is the carrier frequency at which the information is processed. Three reasons for making this modification are as follows:

1. Depending upon the type of detector used in the system, frequency response characteristics indicate that better performance can be obtained at the lower frequencies. This includes the possible phase delays which can be introduced by the detector/amplifier combination as well as the phase variance from unit to unit. In addition, operation of the PbSnTe detector into a current mode amplifier is made easier by the higher amplifier gains available.

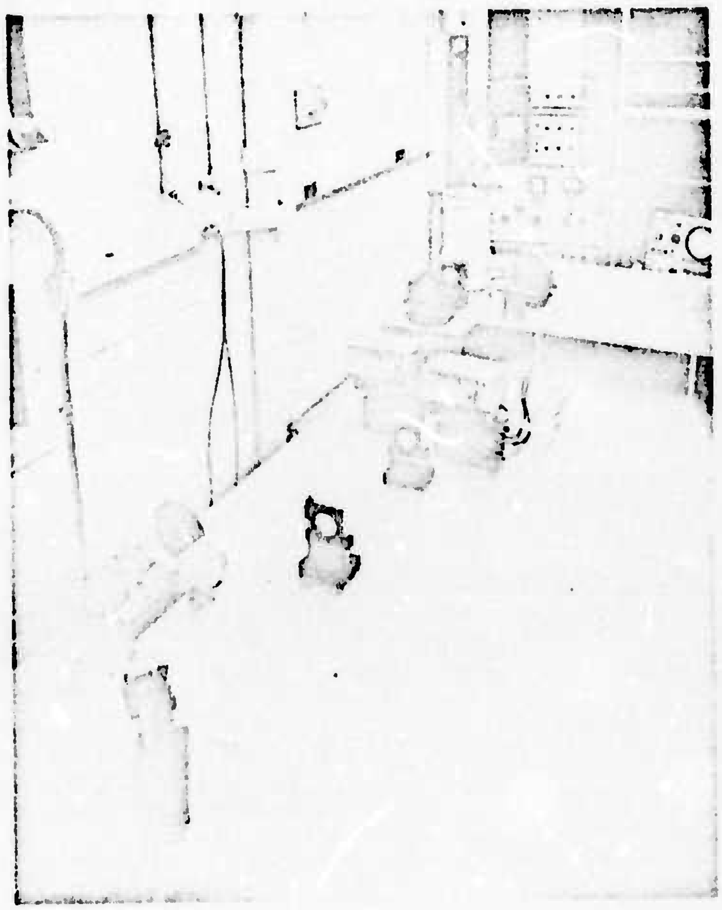


Figure IV-1. One Channel of COAT Array

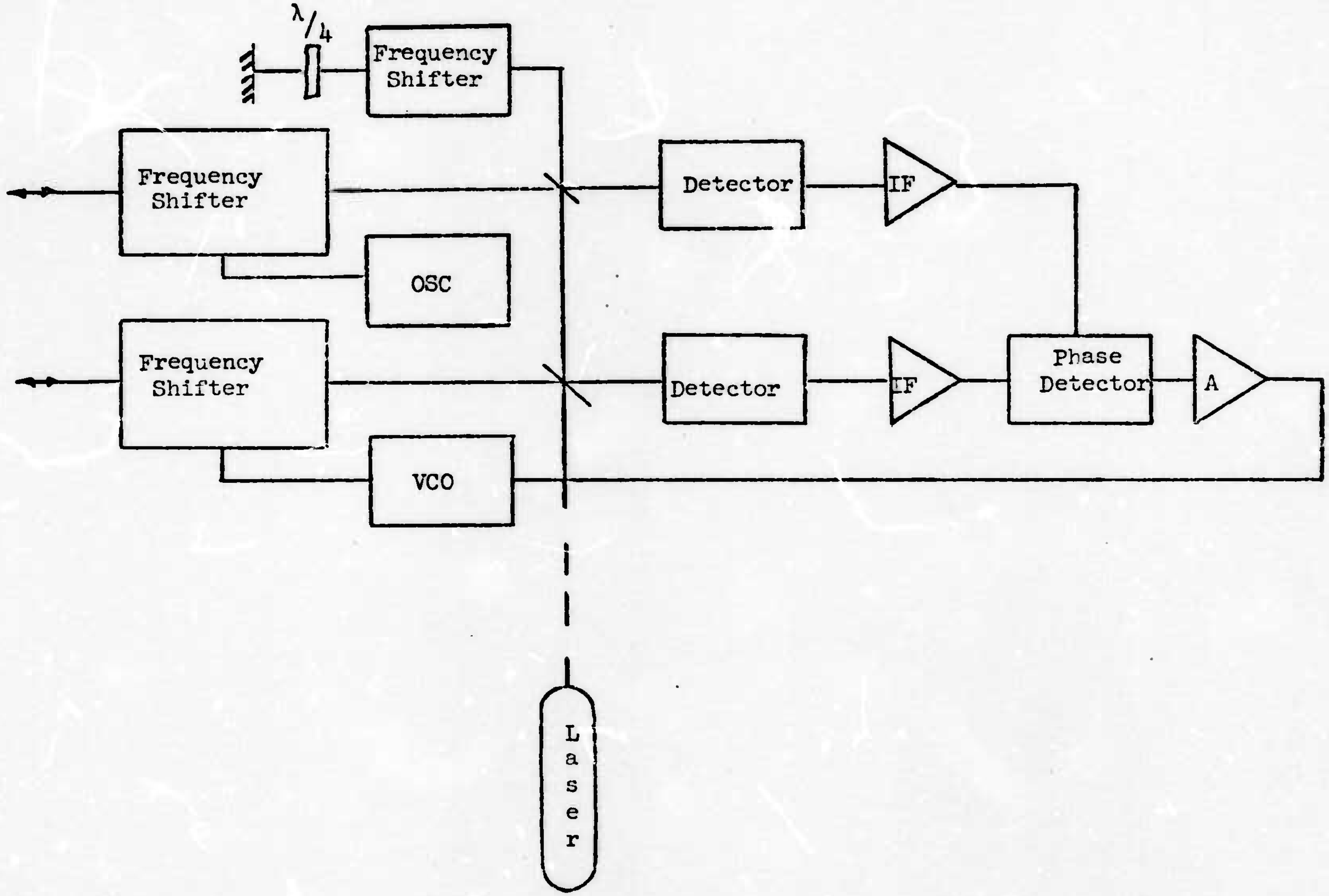


Figure IV-2. Modification of COAT System

2. RFI introduced by the high power drivers for the frequency modulators no longer competes with the received signal. That is, the driver frequencies and second harmonic are at 18 MHz and 36 MHz, and the new carrier frequency is at 4.5 MHz.

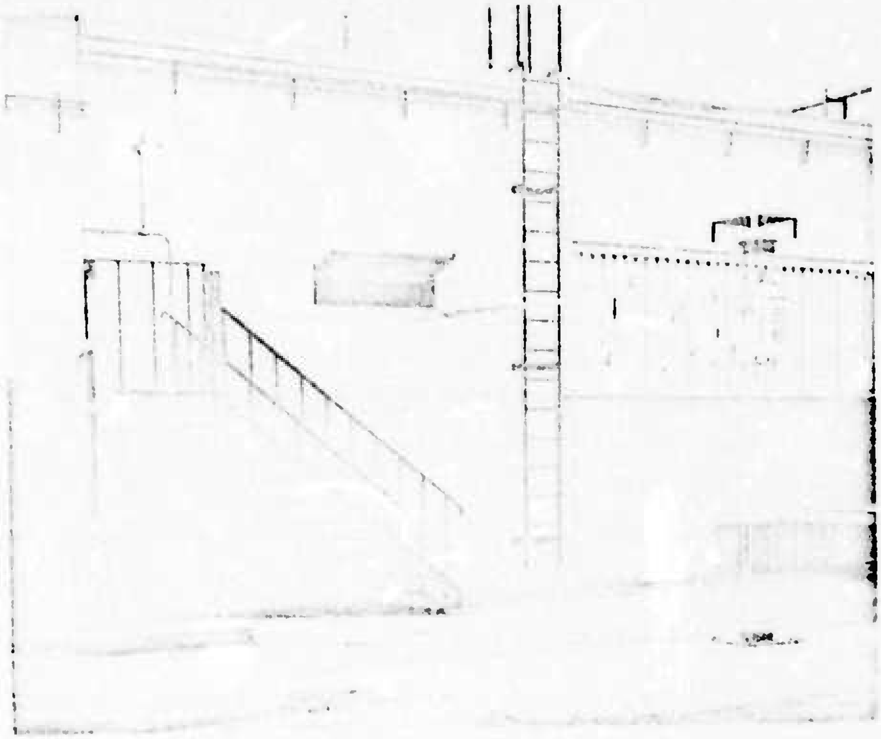
3. Operation of the processing electronics at a lower carrier also facilitates the phase detection process. By reducing the basic information rate from 36 MHz to 4.5 MHz, almost an order of magnitude improvement in any phase errors due to cabling and circuit layout effects has been accomplished.

In the new configuration, an additional frequency shifter has been inserted into the local oscillator arm of the system. The frequency of this unit is set at 15.75 MHz. When combined with the return signal, the information carrier is at 4.5 MHz. That is, 2 x (18.0 - 15.75) MHz. A minor benefit gained from this approach is that the local oscillator power delivered to the detectors is now readily controlled by merely adjusting the RF drive power to the frequency shifter. Thus, optimum detector performance in the heterodyne mode is easily obtained.

B. 1 KM TEST RANGE

All testing to date has been done over the 1 km test range to a "point" target. Figure IV-3 shows the transmitting and receiving sites for this range. Also shown is the instrumentation provided for characterizing the atmospheric parameters. At each site, these instruments have been located as near to the actual transmission path as is practical and yet avoid any anomalous factors which might be introduced by being too close to the buildings.

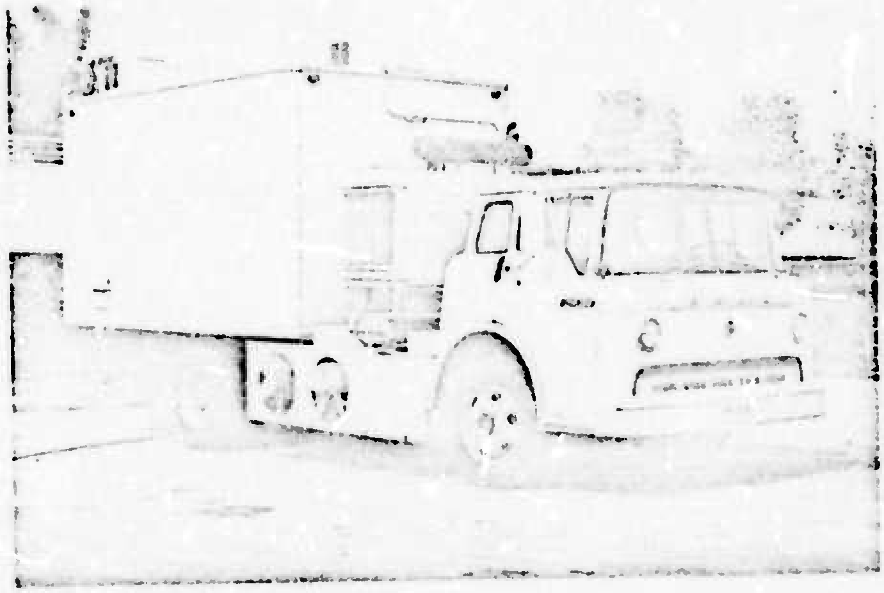
Power and instrumentation at the receiving site is provided by a mobile van equipped for this purpose. Figure IV-4 shows this unit with a diesel-powered generator and some of the instrumentation. All weather parameters including data for determination of the integrated refractive index structure constant over the transmission path will be recorded at this site. All data from measurement of the power distribution at the target for both the adapted and unadapted modes will be recorded for permanent storage.



a) Transmitting Site

b) Target Site

Figure IV-3. Transmitting and Receiving Sites for 1 KM Test Range



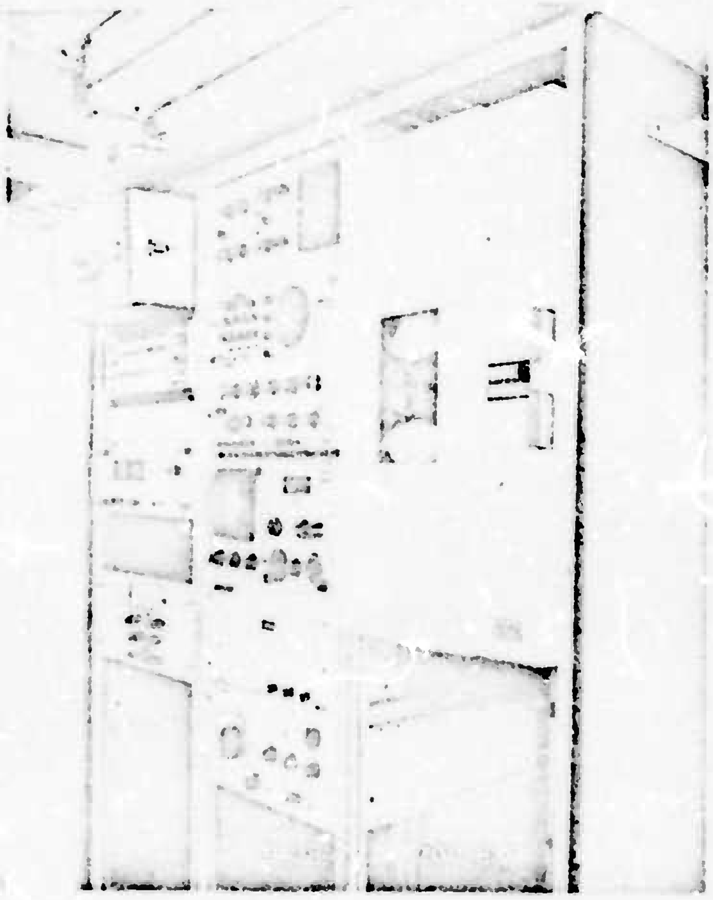


Figure IV-4. Mobile Power and Instrumentation Van for Use at Remote Sites

C. TEST RESULTS

As stated previously, initial tests of the system have been directed towards an evaluation of system components along with determining performance factors such as signal-to-noise ratio. With the system modification as shown in Figure IV-2, 400 mw of power was transmitted to the target from one channel. All components performed as predicted with a resultant signal-to-noise ratio of 60 db using processing electronics having a bandwidth compatible with the final system.

Experience on other programs has shown that systems which employ common transmit/receive optics can be hampered by component scatter from lens surfaces, mounts, etc., unless appropriate precautions are taken. To this end, a polarization discrimination feature was designed into this configuration to reduce these effects. While total discrimination is dependent upon having ideal components, our tests showed the scattered signal to be -55 db below the return signal level. Thus, the system devised to avoid these problems is very effective in that comparable signals would be expected without such an approach.

It should be pointed out that at this time this system has not been optimized. While 60 db of SNR provides plenty of signal margin for both the 1 and 10 km ranges, another 20 db improvement is to be expected. The full array is now being assembled for complete system tests incorporating all of the features incorporated in the single channel.

V. COMPUTER SIMULATION

An important part of the COAT program is manifested in being able to predict not only the operational capabilities of present systems but also the merits of advanced systems. Among the factors which must be considered are the number of elements in the array, the array geometry, the element spacing, element pointing, the element size, strength of atmospheric turbulence, moving targets, and noise perturbations, etc. A computer routine has been developed previously to perform a simulation while permitting any one or all of these factors to be changed. Some of the results obtained for the present program are presented below.

For the data presented here, the simulation was done for a linear array of six elements having apertures of 2.5 cm spaced 3.0 cm on center. All transmitted beams are aligned so as to be parallel; that is, individual pointing of the elements is not considered. The target, located at a range of 1 km, is offset from the center of the array field of view by 10 cm. This is done to demonstrate the fact that as long as the target is in the field of view of the individual elements, the array will deliver maximum energy automatically. This is tantamount to tracking a target within the field of view.

Figure V-1 indicates what the initial distribution of energy at the target plane would be for an array having a Gaussian distribution of power across each element. The initial intensity at the target is seen to be quite low. Upon completing the adaption process, the final distribution of energy is that shown by Figure V-2 (four adaption loops). That is, the distribution has stabilized with maximum power on the target. Figure V-3 indicates how this power buildup took place as a function of time and also indicates the improvement factor to be gained relative to the initial distribution. Fabrication of the array and testing instrumentation to verify these conclusions are now proceeding for full scale tests.

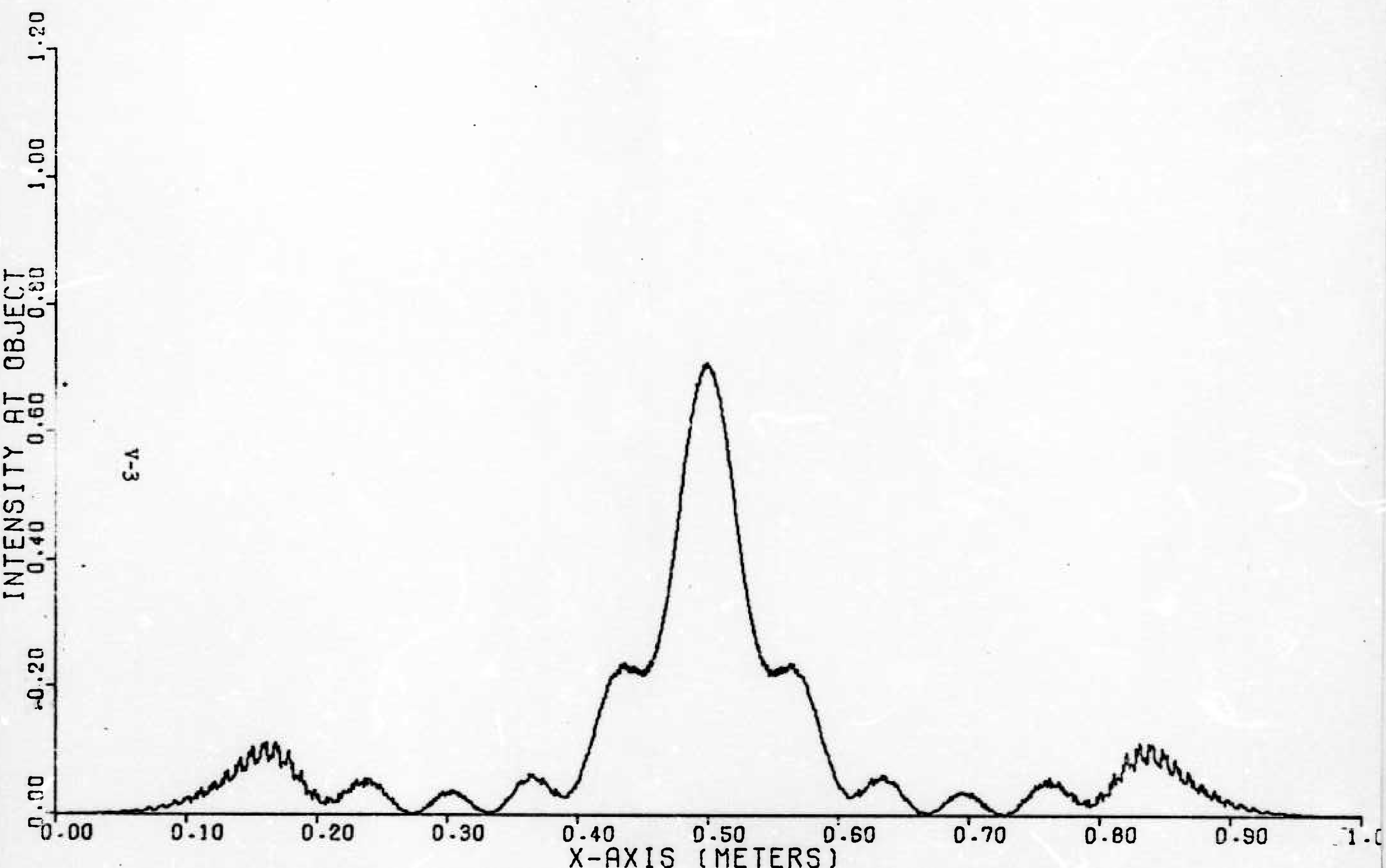


Figure V-1. Initial Distribution at Target Plane, Two Targets Located at 0.4 and 0.6 M with Reflectivities of 0.25 and 1.0, Respectively

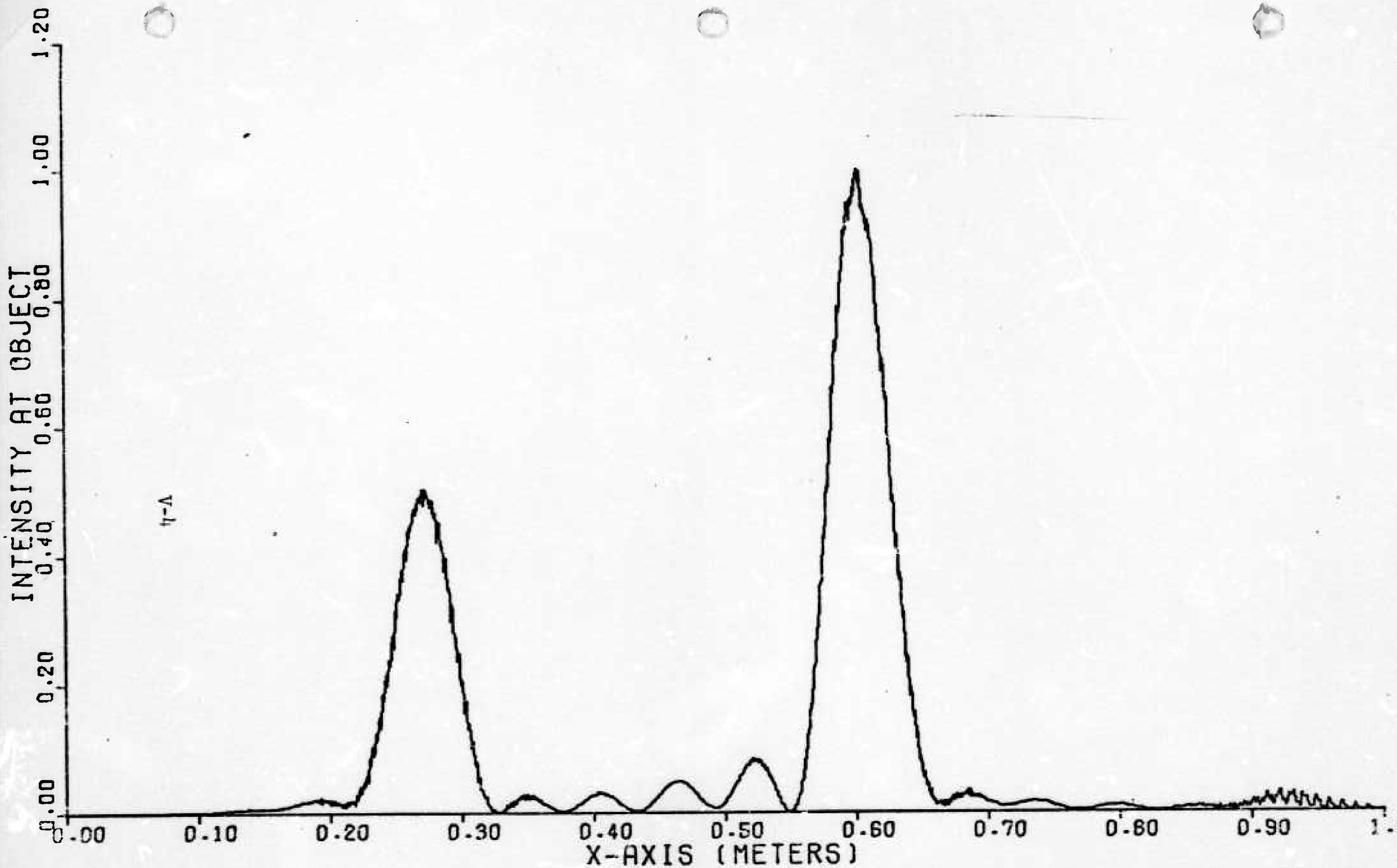


Figure V-2. Energy Distribution at Target After Four Transit Times. Targets Located at 0.4 and 0.6 M with Reflectivities of 0.25 and 1.0, Respectively

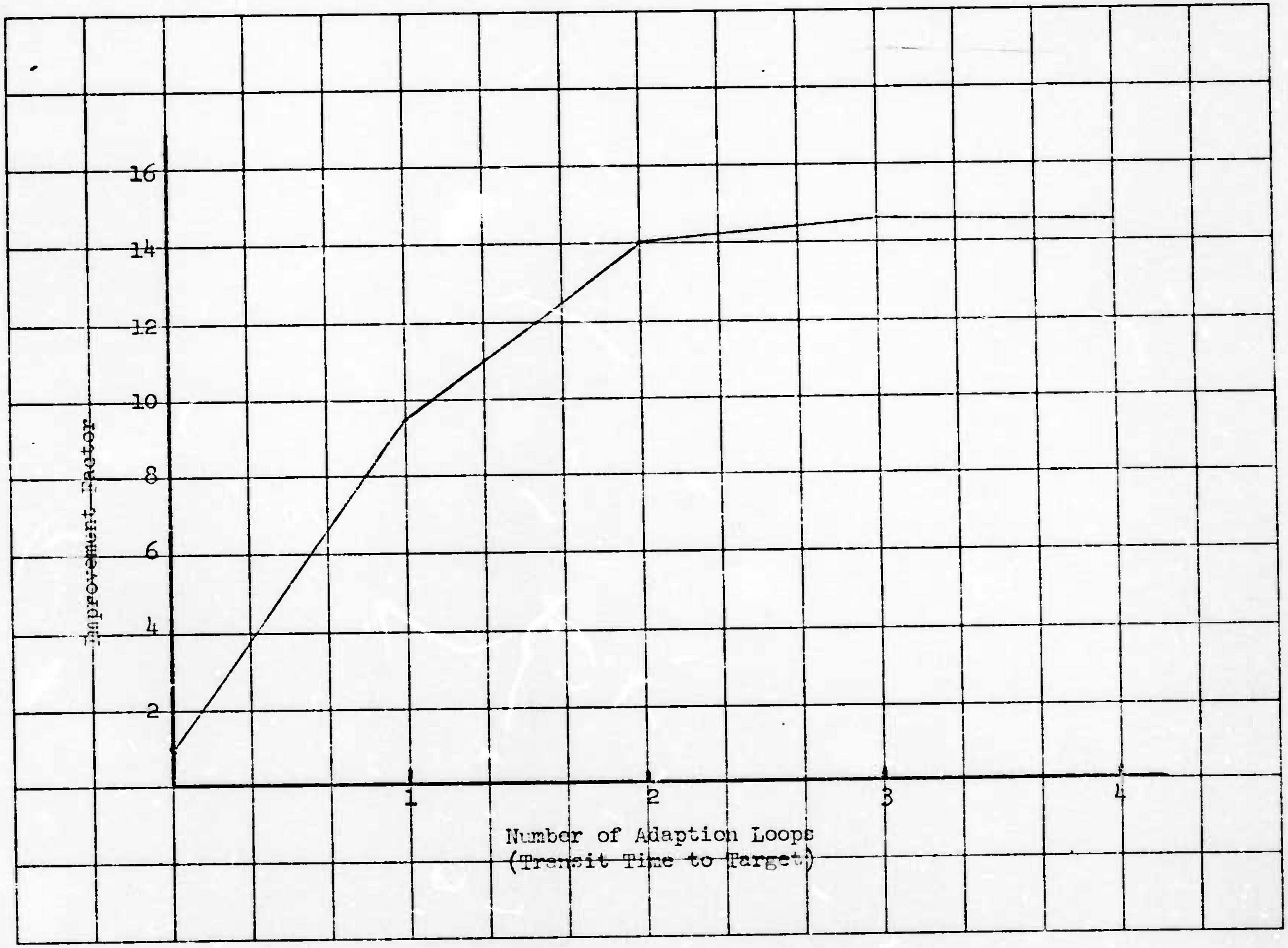


Figure V-3. Improvement in Power Delivered to Target as a Function of Adaption Cycles

UNCLASSIFIED

Security Classification

DOCUMENT CONTROL DATA - R & D		
(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)		
1. ORIGINATING ACTIVITY (Corporate author) North American Rockwell Electronics Group Research Division 3370 Miraloma Ave, Anaheim, CA	2a. REPORT SECURITY CLASSIFICATION UNCLASSIFIED	
	2b. GROUP	
3. REPORT TITLE Coherent Optical Adaptive Techniques (COAT) (U)		
4. DESCRIPTIVE NOTES (Type of report and inclusive dates) Qtrly Tech Report 16 Jul 72 - 16 Oct 72		
5. AUTHOR(S) (First name, middle initial, last name) C. L. Hayes		
6. REPORT DATE 16 Oct 72	7a. TOTAL NO. OF PAGES 62	7b. NO. OF REFS
8a. CONTRACT OR GRANT NO. F30602-72-C-0417	9a. ORIGINATOR'S REPORT NUMBER(S) C72-731.2/501	
b. PROJECT NO. 12790014		
c.	9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report) RADC-TR-72-341	
d.		
10. DISTRIBUTION STATEMENT Approved for Public Release. Distribution Unlimited.		
11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY RADC/OCTM-1/GAFB/NY 13441	

13. ABSTRACT

This report summarizes the design specifications and operating properties of the individual components employed in a 6 element linear COAT experimental array. This array employs a phase conjugate principal to adaptively compensate for both receive and transmitting wavefront aberrations induced by the atmosphere, the target and/or the optical system itself. Inherent in the adaptive operations of the COAT array is its ability to select, focus to and track a single glint in a multiglint moving target environment.

DD FORM 1 NOV 65 1473

UNCLASSIFIED

Security Classification