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PASSIVELY COOLED GLASS CO_2 LASER TUBES FOR SEVERE ENVIRONMENTS

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GSFC — GODDARD SPACE FLIGHT CENTER
GREENBELT, MARYLAND

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ABSTRACT

The objective of this effort was to design a glass CO_2 laser tube that could survive the Titan III C launch environment and at the same time provide adequate thermal conductivity to maintain the wall of the laser tube below $\simeq 50^\circ$ C for efficient lasing.

The approach that was taken to satisfy these requirements was to pot the tube in an aluminum heat sink using a space qualified polyurethane potting material.

Two configurations of the laser tube successfully passed the complete Titan III C qualification level sine and random vibration specification and satisfied the thermal requirements.

Fabrication details and test results are presented that indicate this could be a practical solution for laser tubes used in a severe environment and where flowing coolants are impractical or undesirable.

An experiment is described in which one of these laser tubes was automatically line center stabilized, incorporated into a flight package and flown four times on high altitude balloons.

The flight package not only survived the four flights and terminal parachute drops after each but required no adjustment during the series of tests.

CONTENTS

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ILLUSTRATIONS

TABLES

PASSIVELY COOLED GLASS CO_2 LASER TUBES FOR SEVERE ENVIRONMENTS

I. INTRODUCTION

The use of carbon dioxide lasers has been proposed for spaceborne applications in communications and tracking. The requirements for a laser tube to be used in a space application are that it survive the launch environment, be adequately cooled below $\simeq 50°C$ for efficient lasing without the use of circulating coolants, and exhibit a sealed-off lifetime of approximately 1000 hours for an experiment of one year duration.

Past experience has indicated that those CO_2 laser tubes that exhibited the longest sealed-off lifetimes have been made of glass, typically Pyrex.® An effort was undertaken to design a glass CO_2 laser tube that could pass the qualification level vibration specification for the Titan III C booster, since this launch vehicle is used for some of the large communications spacecraft. The design also had to provide a means of conducting heat away from the plasma region of the tube, particularly the cathode area. Since the use of circulating coolants in space is impractical, a passive means of thermal conduction had to be incorporated.

II. DESIGN AND TEST OF PASSIVELY COOLED GLASS CO_2 LASER TUBES

A. DESIGN AND FABRICATION

The desired output power for a CO_2 laser to transmit from a spacecraft in synchronous orbit to earth is approximately one watt in the TEM_{00q} mode. This parameter dictated the physical dimensions of the laser tube. A three electrode configuration consisting of a central nickel cathode with a tungsten pin welded to it and two tungsten pin anodes was chosen in order to reduce the high voltage excitation requirement to a minimum. The tube, shown in Figure 1, was 30.5 cm long overall with a cathode in the middle and two anodes spaced 10.2 cm on either side of it. The bore of the tube was 5.3 mm with a 2 mm wall thickness and a volume of 6 cc. Beneath the cathode was a tube which connected the bore to a 124 cc gas reservoir used to replenish gas in the bore as it became depleted and prolong lifetime. The ends of the tube were ground at Brewster's angle for NaCl windows. The tube was fabricated from Pyrex except for a small amount of uranium glass around the tungsten pins to form a graded seal. The entire tube assembly was oven-annealed at 1040°C for approximately one hour to relieve stresses induced during fabrication.

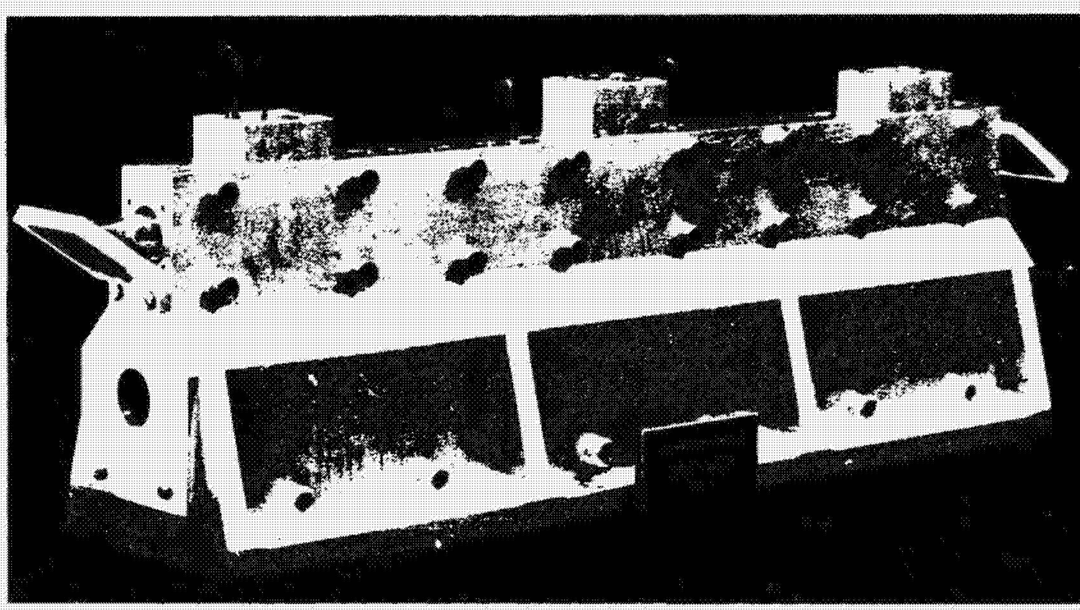

Figure 1. First Configuration of Laser Tube to Be Vibration Qualified

A close fitting aluminum heat sink was designed to fully enclose the tube. The bore of the heat sink was made 12.7 mm to provide a uniform 1.7 mm clearance around the plasma region of the tube and slightly higher clearances elsewhere.

Teflon rings were used on the ends of the tube to center it in the heat sink and Solithane 113® was used to fill the voids between the tube and heat sink. Solithane 113 is a versatile, space qualified, polyurethane potting compound whose formulation can be varied to yield Shore "A" hardness values from 15 to 87. Formula 12, which has an ultimate hardness of 80, was used to pot the laser tube assembly. After potting, the whole assembly was heat treated at 70°C for 24 hours to cure the potting material. Prior to potting, the interior surfaces of the heat sink were coated with a mold release agent to permit later disassembly of the heat sink and inspection of the tube after vibration testing. This tube successfully passed the vibration specification. Details of this and other testing are covered in section II B.

After the initial success of the previous tube a second configuration, shown in Figure 2, was designed. The geometry of the main laser bore and electrodes was the same as before but the single large gas reservoir was changed to two smaller ones located on either side of the main bore. This resulted is a more compact design with a lower profile that was more suitable for incorporation

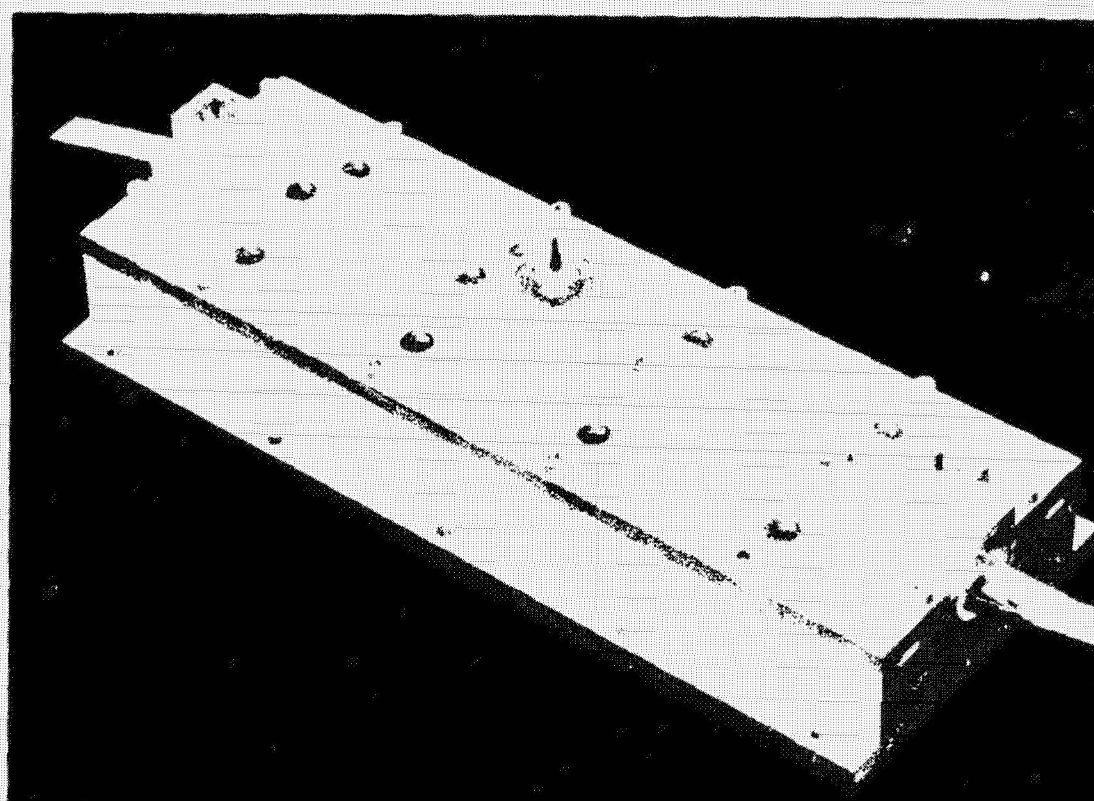

Figure 2. Second Configuration of Laser Tube to Be Vibration Qualified

into a system with other optical elements. The heat sink for this tube also provided a 1.7 mm clearance around the plasma region and it was potted with formula 12 Solithane 113. Due to the added complexity of this tube a special jig was used to keep the various parts of the tube in alignment during fabrication. The same jig was also used to hold the tube while grinding the Brewster angles.

B. *TESTING*

Before being subjected to vibration, the first configuration of the laser tube was equipped with NaCl windows and its performance as a laser was checked in the lab. The test was performed in a stable invar optical cavity using a 95% reflectance germanium output mirror. This mirror was plano-plano and AR coated on the outside surface. The rear mirror of the cavity was a 100% gold coated mirror of 1445 mm radius of curvature.

This tube was not sealed off because of the lack of a proper processing station at the time and the desire to proceed with the vibration test. Since it had only one external tubulation attached to the reservoir for gas filling, it was operated in what might be called a "replenishment" mode as opposed to a more conventional flowing gas system in which the laser tube has gas connections at both ends and gas is flowed through the bore at a fairly high rate. Under these conditions, the electrical operation of the tube approaches that of a sealed off tube of the same design and gas constituency.

A gas mixture of 16.7% CO_2, 16.7% N_2, and 66.6% He at 25 mm Hg pressure was used to test the tube and the following results were obtained:

Power output:	1.07 watts TEMooq mode
Power input:	2370V. @ 5 ma each side
Ballast resistance:	200K Ω each side

This gas mixture is one that is in general use in the lab for a variety of CO_2 lasers and does not represent an optimized mixture for this particular tube.

Figure 3 shows a diagram of the test set-up used to make measurements on the tube. Figure 4 is a graph of power output and tube efficiency vs. plasma current. It may be seen that one watt of power output was obtained at 5 ma plasma current, which was a design goal. With an optimized gas mixture and the addition of Xenon the power output and efficiency could be raised, resulting in a comfortable operating margin. Figure 5 shows a graph of tube wall temperature, heat sink temperature, and tube power input vs. plasma current. In order to be able to make the temperature measurements, a copper vs. constantan thermocouple was potted into the assembly on the tube wall adjacent to the cathode which is the hottest part of the tube. The heat sink temperature was held nearly constant by water cooling the base plate on which it was mounted. A sharp rise in tube wall temperature was observed but it did not exceed the 50°C point. It should be noted that since mold release was used in the heat sink for inspection purposes, intimate contact of the potting material with the heat sink was not possible. This could cause a loss of thermal conductivity and account for the rise.

After functional testing in the lab was completed, the tube assembly was vibration tested to Levels I and II of the sinusoidal and random vibration specifications given in Tables 1 and 2. The tube was visually inspected after each run to determine if any damage had occurred to the electrode domes or around the windows. After the sequence was completed in each axis, the side of the

Table 1

Sinusoidal Vibration Specification for Titan III C Booster

Test Level	Axis	Frequency (Hz)	Input Level	Sweep Rate	Test Time
Design Qualificiation Test I (Equipment Nonoperating)	Thrust and Lateral (Z-Z, X-X, and Y-Y)	5 to 22 22 to 200 200 to 2000	0.5-inch double amplitude constant displacement 12.0 g (0-to-peak) 5.0 g (0-to-peak)	2 octaves minute	13.0 minutes (total)
Flight & Ground Acceptance Test II (Equipment Nonoperating)	Thrust and Lateral (Z-Z, X-X, and Y-Y)	5 to 18 18 to 200 200 to 2000	0.5-inch double amplitude constant displacement 8.0 g (0-to-peak) 3.3 g (0-to-peak)	4 octaves minute	6.5 minutes (total)
Flight & Ground Acceptance Test III (Equipment Operating)	Thrust and Lateral (Z-Z, X-X, and Y-Y)	20 100 200 400 600 800 1000	Velocity (cm sec, rms) 3.9×10^{-2} 7.8×10^{-3} 3.9×10^{-3} 2.0×10^{-3} 1.3×10^{-3} 1.0×10^{-3} 7.8×10^{-4}		

Table 2

Random Vibration Specification for Titan III C Booster

Test Level	Axis	Frequency (Hz)	PSD Level (g^2/Hz)	Overall Acceleration (g-rms)	Test Time
Design Qualificiation Test I (Equipment Nonoperating)	Thrust and Lateral (Z-Z, X-X, and Y-Y)	20 to 250 250 to 2000	0.0010 to 0.16 increasing from 20 Hz at the rate of 6 db octave 0.16	17.0	4.0 minutes each axis (Total 12 minutes)
Flight & Ground Acceptance Test II (Equipment Nonoperating)	Thrust and Lateral (Z-Z, X-X, and Y-Y)	20 to 250 250 to 2000	0.00046 to 0.07 increasing from 20 Hz at the rate of 6 db octave 0.07	11.3	2.0 minutes each axis (Total 6 minutes)

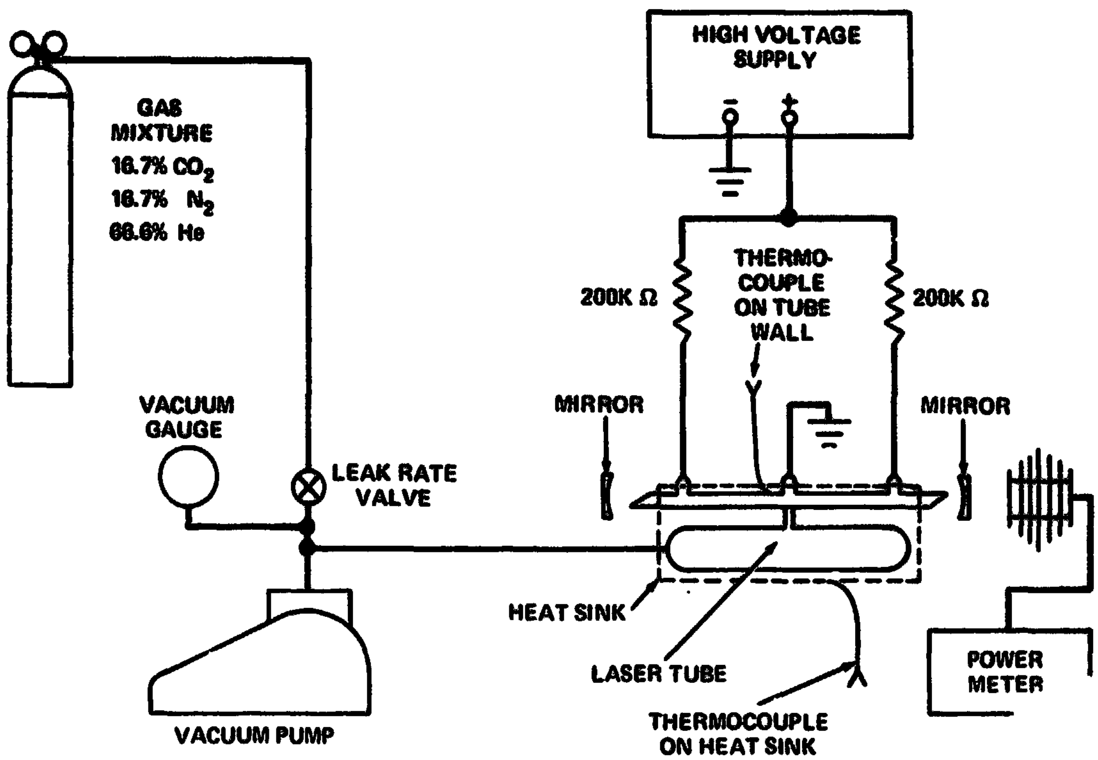

Figure 3. Laboratory Test Set-Up for Laser

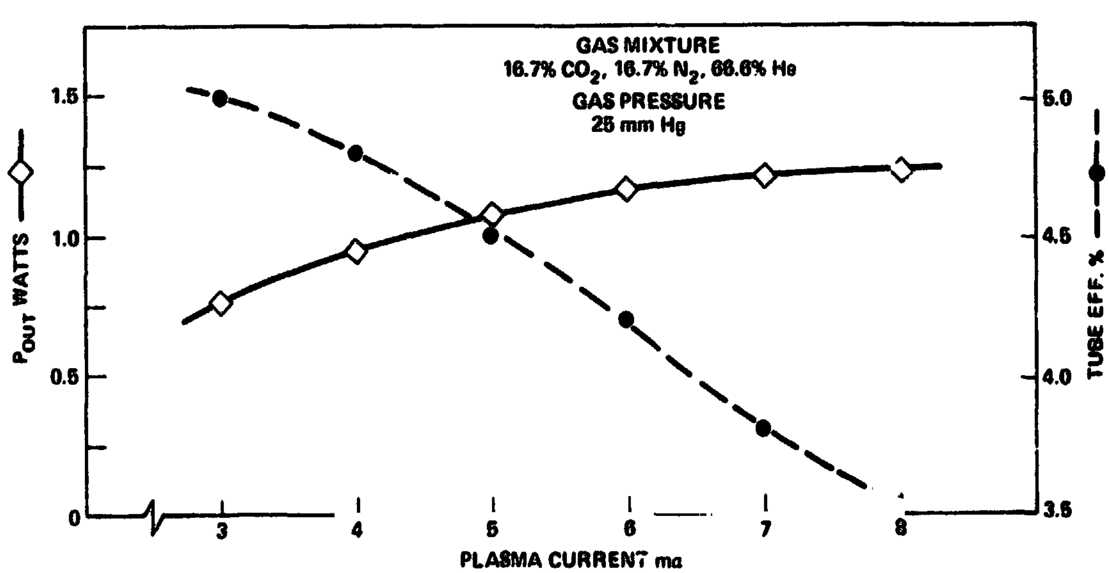

Figure 4. Power Output and Tube Efficiency vs. Plasma Current

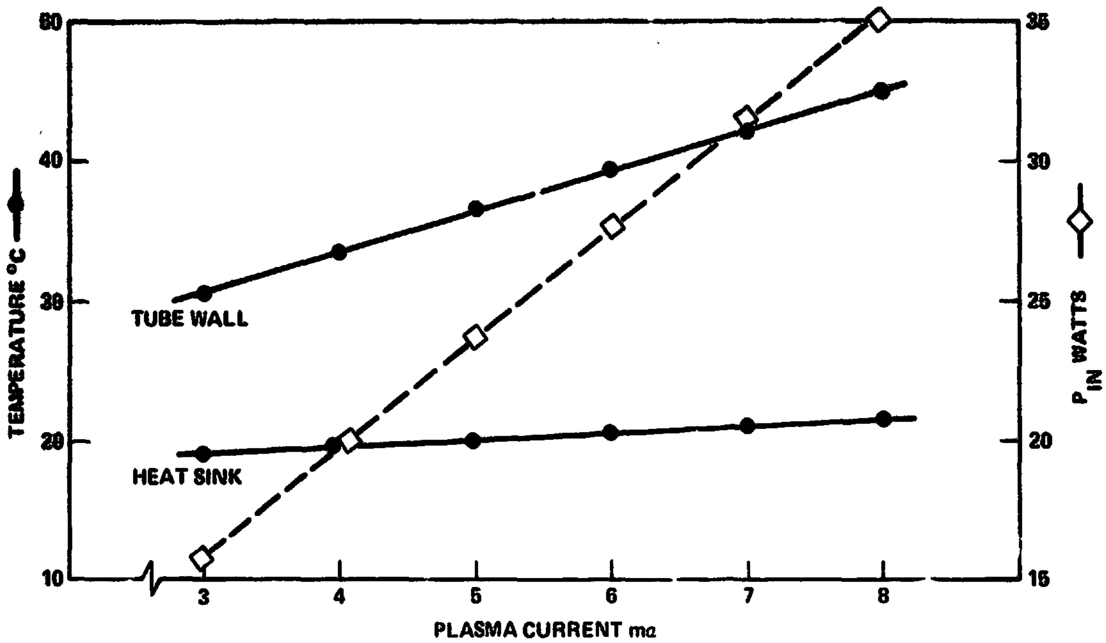

Figure 5. Tube Wall Temperature, Heat Sink Temperature, and Tube Power Input vs. Plasma Current

heat sink, as shown in Figure 6 was removed and the entire tube was inspected. No damage was found and the tube was performance tested again in the lab. No changes in operating characteristics were noted.

III. APPLICATION OF AUTOMATICALLY STABILIZED LASER SYSTEM

An opportunity to apply one of the newly developed tubes presented itself in the form of the BAPE II (Balloon Atmospheric Propagation Experiment II) which was scheduled for the Fall of 1971. This was a series of high altitude balloon flights designed to measure propagation effects of the atmosphere at various laser wavelengths. It was desirable to have a CO_2 laser on board the balloon pay load and the passively cooled tube offered the best approach to meet this requirement. A number of sealed off tubes of the second configuration had been obtained from GTE Sylvania, Inc. under NASA Contract NAS 5-21606 for the purpose of life test studies. Two of these tubes were diverted to the BAPE II experiment. One of the tubes was used in the ground station receiver and the other was used in the flight package. The latter will be discussed in detail here.

Figure 6. First Configuration of Laser Tube with Side of Heat Sink Removed for Inspection

The primary purpose of the on-board system was to attempt to establish an air-to-ground CO_2 laser heterodyne link. In order to accomplish this, the airborne system had to be fully automatic in its operation. This meant that when power was applied to the system, it had to tune the laser to the desired line and stabilize it there using line center dither techniques.

Figure 7 shows a block diagram of the system. The function of the laser control electronics is to produce a scan of the laser's operating frequencies until the desired frequency is obtained. In this case, this corresponds to obtaining operation on the P20 line of the laser at a center frequency of 28,306,251 MHz. After the scan sequence has tuned the laser to within nominally ±30 MHz of the final desired operating frequency, the laser control electronics must generate appropriate signals to cause the laser to seek and remain at the peak of the power profile of the operating line, which also corresponds to the center frequency of the line.

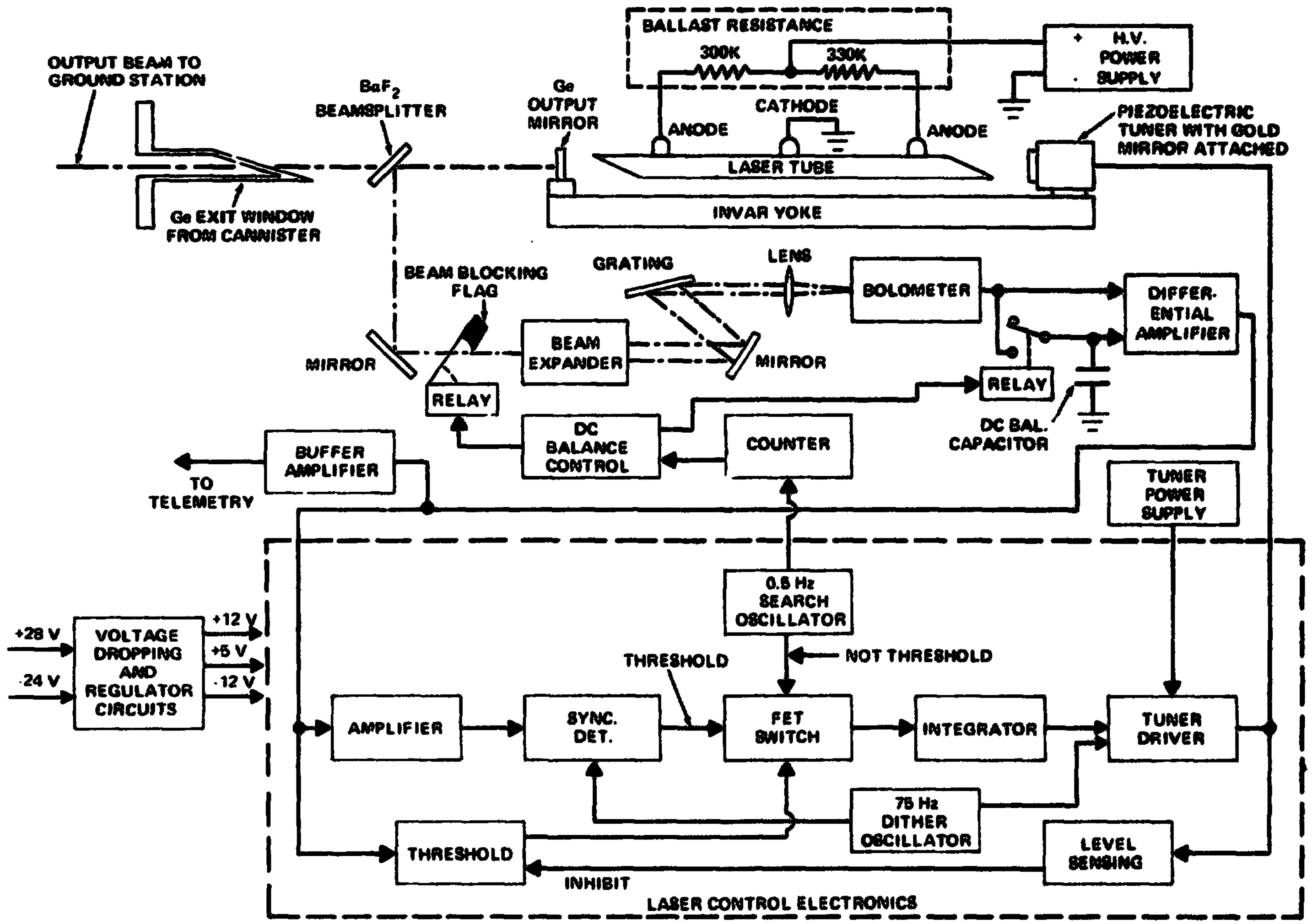

Figure 7. Block Diagram of BAPE II Flight Package

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Operation is initiated by the application of power from the balloon payload batteries. A portion of the laser output beam is taken off by a barium fluoride beam splitter and passed through a beam expander to efficiently illuminate an optical grating. The output of the grating goes through a lens and is focused on a bolometer. Since the area of the active flake of the bolometer is quite small and the barious frequencies from the laser are spatially dispersed by the grating, the bolometer and grating can be mechanically oriented so that only the P20 line will focus on the active flake. Figure 8 shows a typical bolometer output as the laser is tuned by the piezoelectric tuner through its operating range. The pulses are produced as the laser is tuned across the P20 line and occur every half wavelength or 5.3 micrometers of piezoelectric tuner travel.

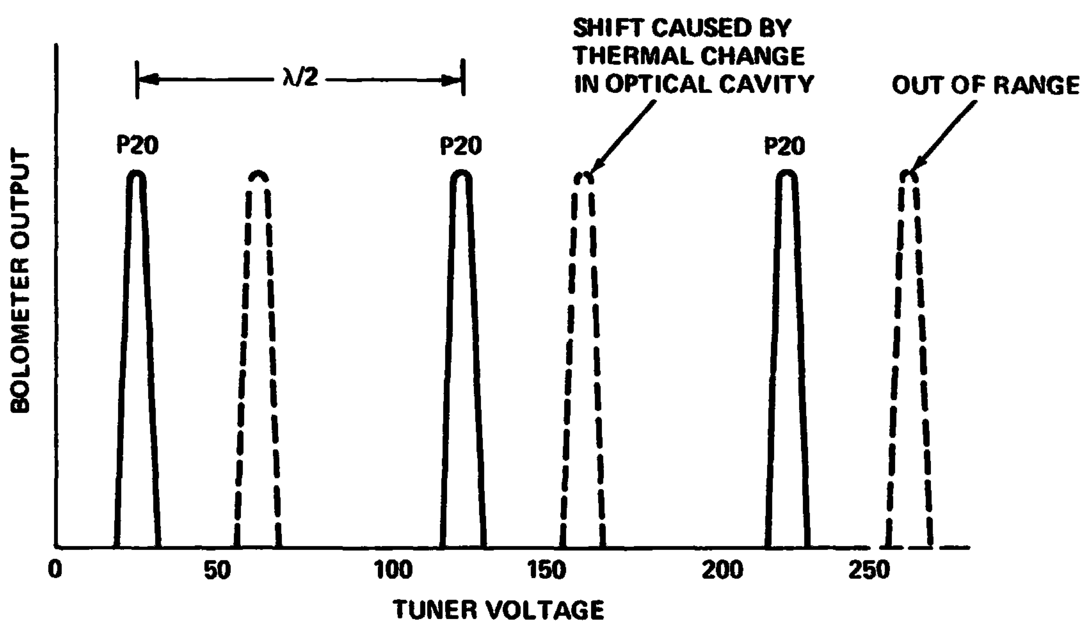


Figure 8. Typical Distribution of P20 Lines within Tuner Range

With no power from the bolometer, the output from the threshold circuit is a NOT THRESHOLD, which throws the FET switch to connect the search oscillator into the integrator. The search oscillator has a 0.5 Hz square wave which becomes a triangle wave when passed through the integrator. The triangular wave is amplified in the tuner driver and is applied to the piezoelectric bender bimorph. When the laser cavity is tuned to the proper wavelength, the bolometer delivers a voltage which triggers the threshold circuit. This action throws the FET switch into position for dither stabilization.

The dither oscillator is operating at 75 Hz and is fed to the input of the tuner driver which produces a frequency modulation of the laser at the dither frequency. Because of the shape of the laser's gain curve, shown in Figure 9, the frequency modulation is accompanied by amplitude modulation at twice the

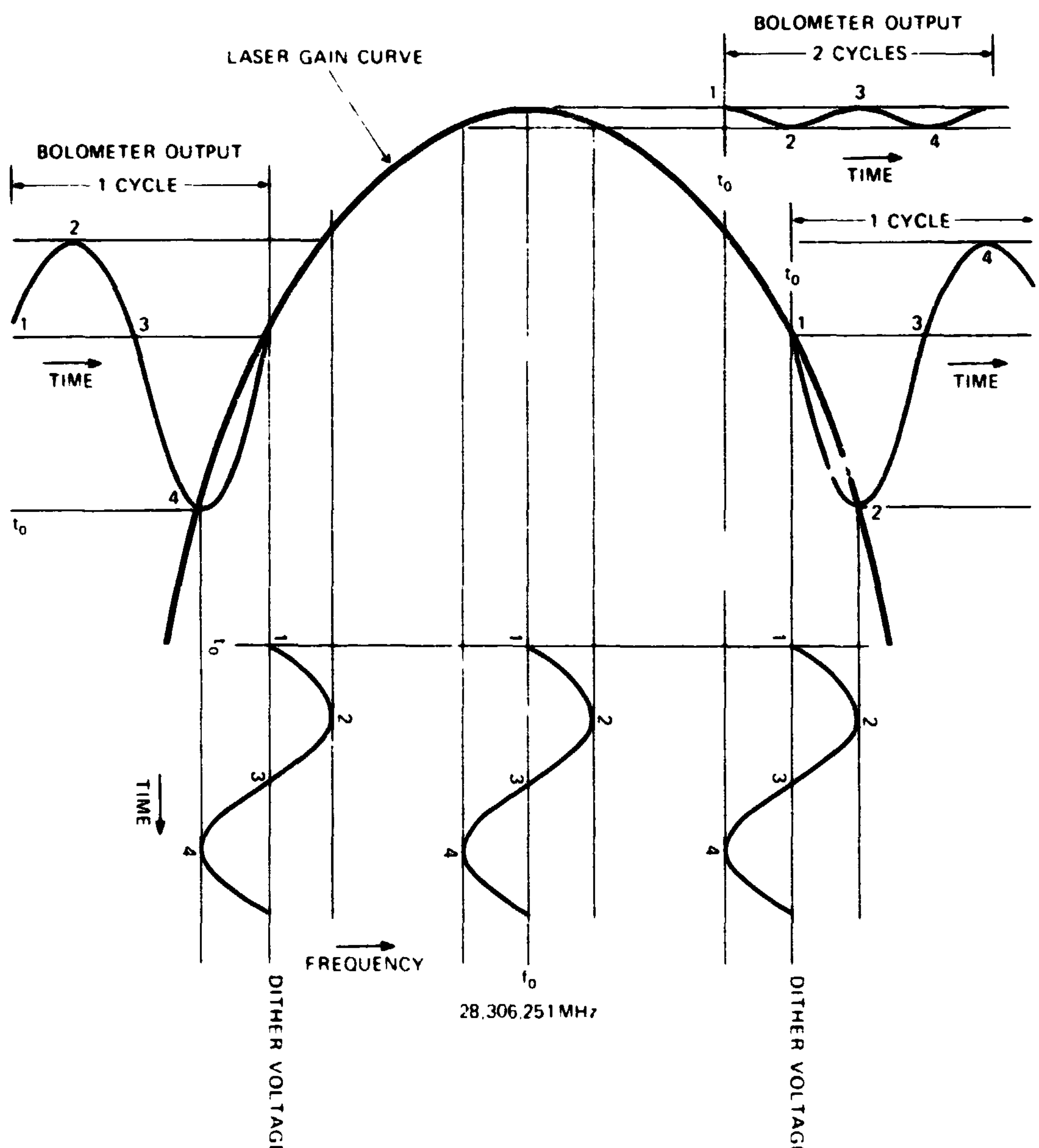


Figure 9. Generation of Frequency Discriminant from Laser Gain Curve

dither frequency when the laser is centered on the line. If the laser is operating to either side of the line center the laser is amplitude modulated at the dither frequency but with differing phase. By detecting the amplitude modulation in synchronism with the dither frequency reference a discriminator-like curve is generated that has a zero at line center. The tuner is driven until the error signal is nulled and the laser is therefore operating at line center.

A level sensing and inhibit circuit is included to prevent lockon at either extreme of the range of the tuner driver and prevent lockon on partial line profiles. A thermal change in the optical cavity can cause a shift of the location of the P20 lines within the tuner range. Should the laser be locked on a line that drifts close to either extreme of the tuner range the sensing circuit causes the laser control electronics to break lock and seek another line within the tuner range. This is also illustrated in Figure 8.

A problem was encountered with the bolometer that was available for the experiment which necessitated some additional circuitry. The bolometer contains a compensating flake, whose resistance closely matches the active flake, mounted out of the field of view of the bolometer. The purpose of this flake is to compensate for changes in the output of the active flake due to ambient thermal changes and not signal input. A wiring diagram of the bolometer is shown in Figure 10. Since the compensator flake did not exactly track the active flake a small error voltage, on the order of a few millivots, was built up at the bolometer output. It was necessary to have a X100 amplifier at the bolometer output to drive the control electronics and this error signal after amplification was sufficient to overcome the threshold setting and cause a false lock.

The solution that was used to overcome this problem was to put a differential amplifier at the output of the bolometer and periodically balance the two inputs in the absence of a signal. A high Q capacitor was connected to the second input of the differential amplifier and a relay was used to short the two inputs together. Simultaneously, another relay with a small flag attached blocked the laser beam input to the bolometer. Thus, the only voltage appearing at the output of the bolometer was due to thermal error between the two flakes. With the two inputs shorted, a charge equal to the error voltage is placed on the capacitor. When the relays are opened and normal operation resumed, the charge on the capacitor cancels the thermal error voltage in the amplifier and the only voltage appearing at the amplifier output is due to laser signal input to the bolometer. The capacitor was 5.6 microfarads and the input impedance to the amplifier was 10^{11} ohms. This long RC time constant allowed proper operation of the system over fairly long intervals of time before rebalancing.

The rebalancing interval was established by taking an output from the 0.5 Hz search oscillator into a divider chain. The output of the divider chain went

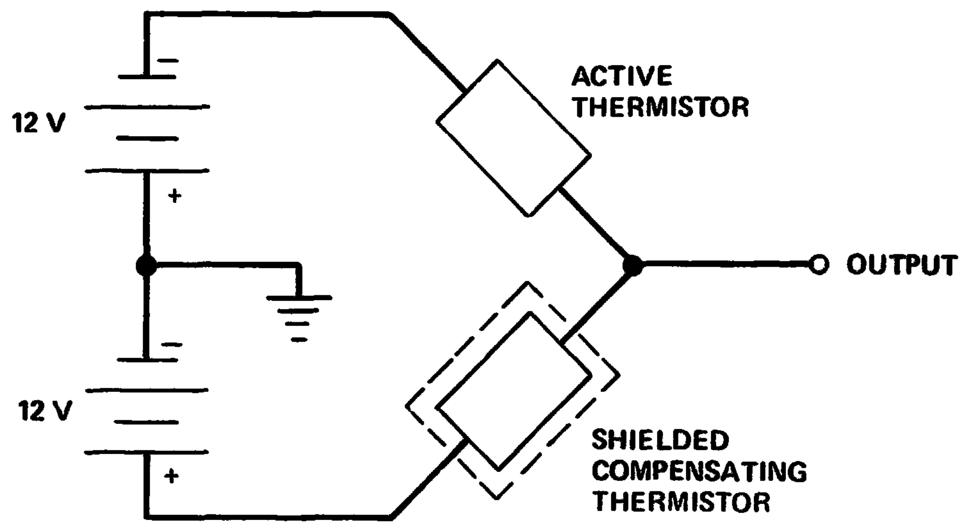
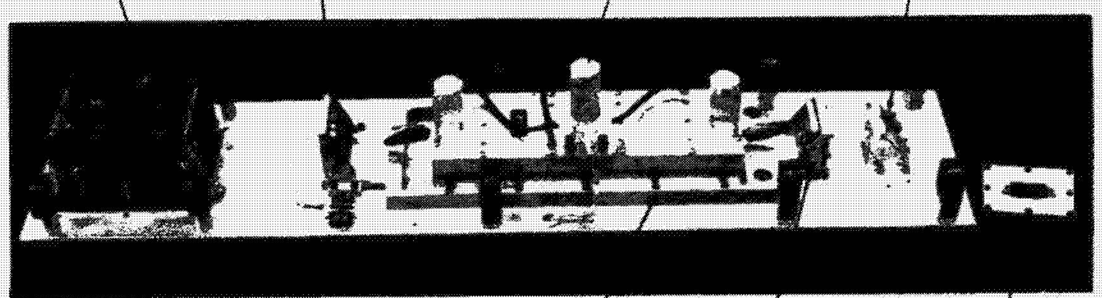


Figure 10. Bolometer Wiring Diagram

to a DC balance control circuit to operate the relays. Various intervals up to 512 seconds were possible with this arrangement. An interval of 256 seconds was used during the flight experiments. During the balancing interval the system would break lock and go into search mode. The interruption was not considered serious in this particular application since it only lasted about two seconds. In applications where the interruption cannot be tolerated, more restrictive specifications on the bolometer can eliminate the problem.

The various components of the system were mounted on a 71.1 cm L. x 15.2 cm W. x 1.3 cm thk. aluminum base plate and this in turn was mounted in a cylindrical stainless steel cannister 76.2 cm long and 16.8 cm in diameter that was hermetically sealed on the ground to preserve a one atmosphere internal pressure. Figure 11 shows a top and bottom view of the base plate with major system components identified. Figure 12 shows a view of the base plate partially inserted into the cannister and Figure 13 shows the cannister after it was sealed.

The cannister was located in the elevation axis assembly of the balloon payload as shown in Figure 14. A mirror mounted on the outside of the cannister turned the beam 90° and directed it through a slot in the elevation axis assembly to the ground receiver. Also located in the elevation axis assembly was a star tracker that locked on an argon laser beacon signal from the ground station and directed the azimuth and elevation servos to keep the laser beam pointing toward the ground station. The CO_2 laser beam was bore sighted to the star tracker before flight.



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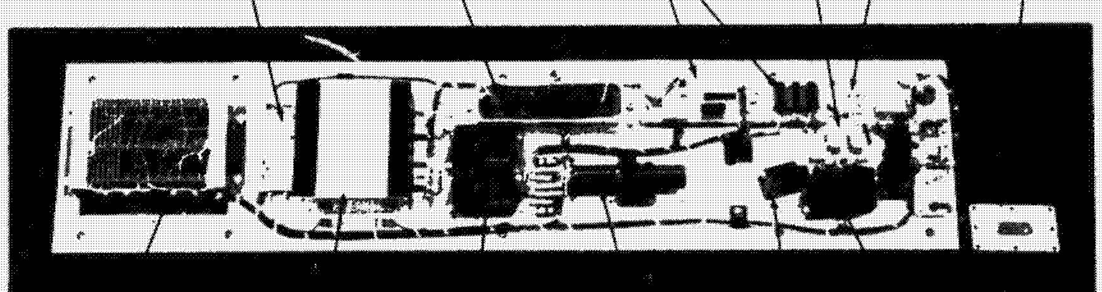

(b)

Figure 11. Top and Bottom Views of BAPE II Flight Package Baseplate with Components Mounted

Figure 12. Base Plate Partially Inserted in Cannister

Figure 13. Cannister After Sealing

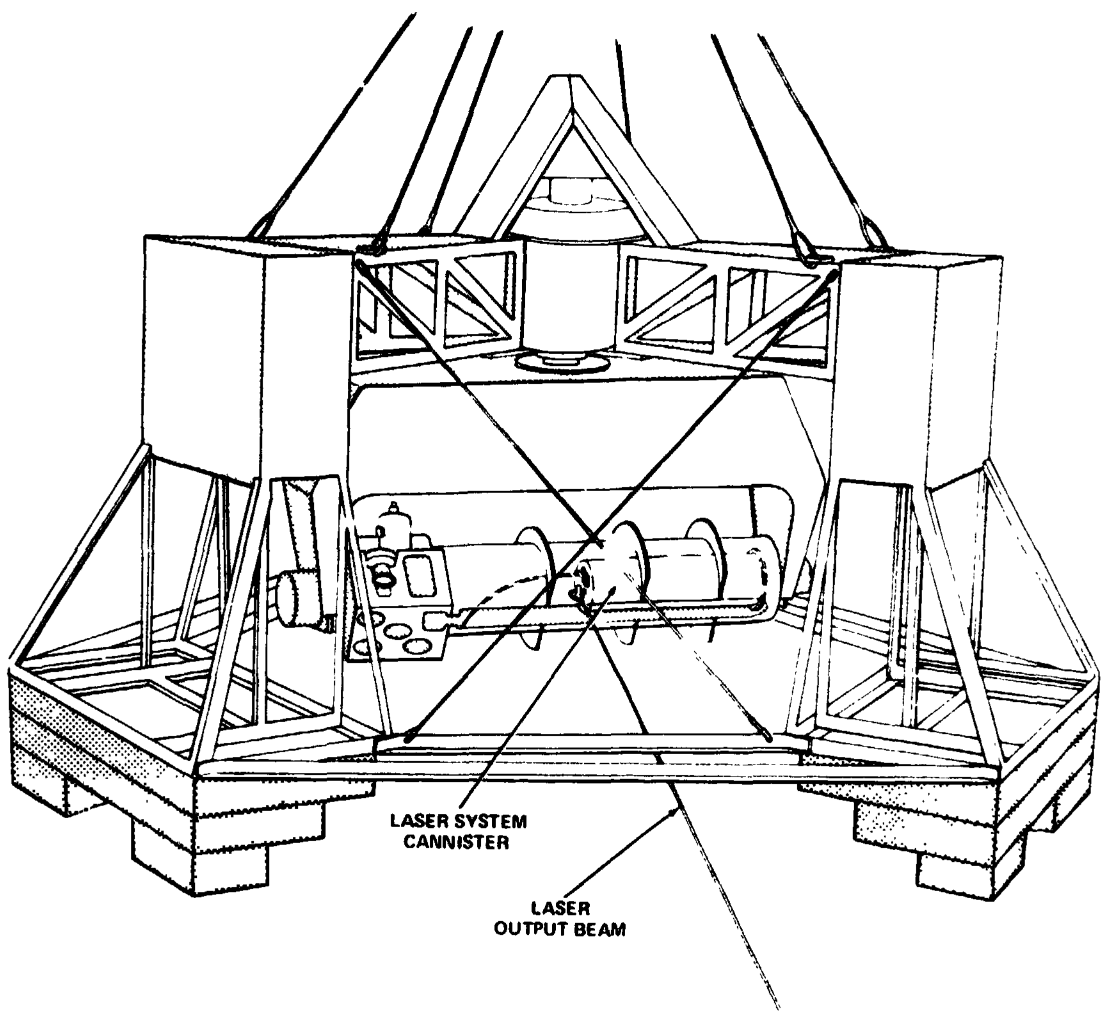

Figure 14. Location of Laser System Cannister
in BAPE II Elevation Axis Assembly

During the month of September 1971 the flight package was flown four times aboard high altitude balloons launched from Holloman Air Force Base near Alamogordo, New Mexico. Due to balloon failure early in the first flight and erratic flight paths on the next three flights that kept the balloons out of range of the ground station, it was impossible to establish the heterodyne link as originally intended. However, telemetry data from the airborne package indicated normal operation up to altitudes of 21 kilometers and temperatures as low as -60 C.

Figures 15a and 15b show two samples of this telemetered flight data recorded at the ground station. Figure 15a shows the initial turn-on of the laser and the large temperature differential build-up at the bolometer output during the warm-up period. After 256 sec. the DC balance control initiates a re-balancing (identified as "reset" on the data) of the output of the differential amplifier and normal operation is achieved. It may be seen at the second re-balancing that a small thermal error is nulled out. After this no further thermal error build-ups are noted during the subsequent re-balancing intervals. Figure 15b shows approximately one half hour of continuous data during which the laser power output remained constant and no thermal errors were noted.

The method of returning the payload to the ground after a flight was by parachute. The airborne laser package survived four of these terminal parachute drops and the payload was once dragged approximately 305 meters through a field when the parachute failed to detach itself upon impact with the ground.

During the whole series of flight tests, no internal adjustments of the laser package were required. The only external adjustments made were minor ones to re-boresight the cannister to the startracker in the payload elevation axis.

IV. CONCLUSION

Glass CO_2 laser tubes can be fabricated that are sufficiently rugged to survive severe thermal and vibration environments and continue to function properly.

V. ACKNOWLEDGEMENTS

The authors wish to thank George Bergen and Robert Harris of the Goddard Space Flight Center Optics Branch for their expert advice and craftsmanship in the fabrication of the laser tubes and Carroll Clatterbuck and Dr. Benjamin Seidenberg of the Materials Engineering Branch for their many helpful suggestions and generous assistance in potting the tubes in the heat sinks.

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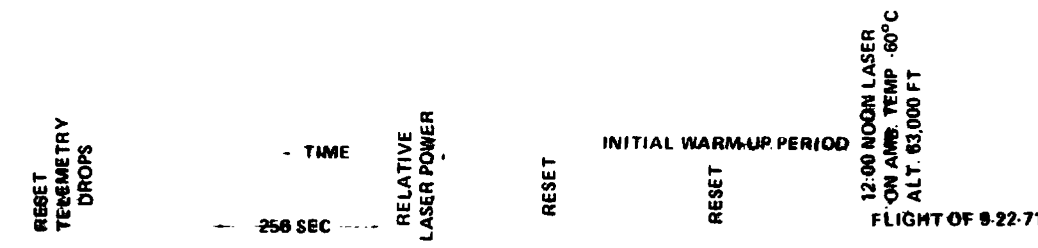

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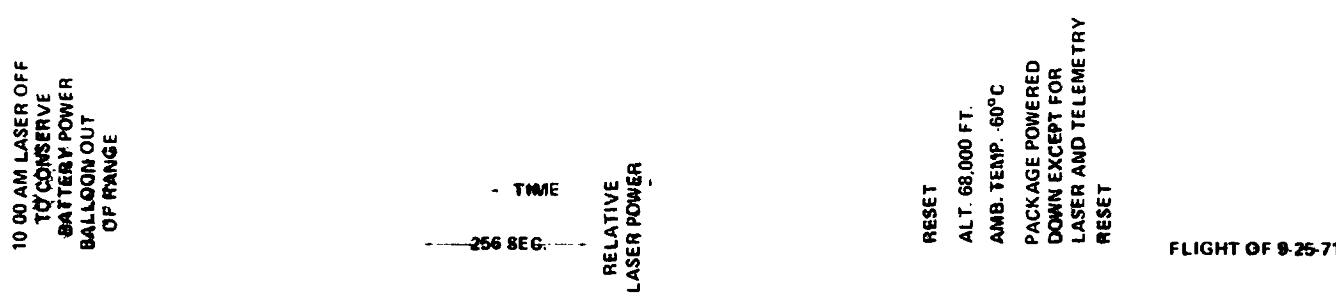

(b)

Figure 15. Telemetered Flight Data Recorded at Ground Station