CONTRACT REPORT ARBRL-CR-00526

LASER BALLISTIC SENSOR DEVELOPMENT

Prepared by

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March 1984

US ARMY ARMAMENT RESEARCH AND DEVELOPMENT CENTER
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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The results of a series of experiments to measure the yawing motion of a projectile in flight are reported. A laser angular measurement system is used which illuminates a reflector assembly mounted on the projectile. The assembly consists of a special holographic grating and a 6.4 mm cube corner reflector. The assembly generates interference fringes that are used to measure angular position. Tests demonstrated that the system survived launch, acquired data, and provided results which agreed with simultaneous ballistic range measurements.

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I. SUMMARY

The measurement of projectile motion, yaw and position in time provides the information required for the determination of aerodynamic properties such as lift, drag, and overturning moment coefficients. These are essential elements in the design of advanced shells for improved flight performance and to the construction of firing tables and aiming data.

At present, data is acquired in ballistic ranges where photographs of projectiles are made at numerous stations along the trajectory. The equipment necessary to obtain the photographs is extensive and significant manhours are required for maintenance and operation. Data reduction is now performed at optical benches at high cost. Because of this, a new technology is needed to reduce costs while maintaining accuracy, with increased data quantity.

This contract is an examination of the feasibility of transferring an established technology developed at the Boeing Aerospace Company to the measurement of projectile angular motion. The technique employs a laser and associated detectors to measure the angular orientation of a small reflector assembly mounted on the object of interest. The reflector assembly consists of a special holographic grating and a 6.4 mm cube corner reflector. When illuminated with a laser, the reflector assembly generates interference fringes that are used to measure angular position.

An existing Boeing angle measurement system was modified for the feasibility test at the Ballistic Research Laboratory's Aerodynamics Range. The laser equipment was shipped to BRL in May 1983 for a 5-day test. Mounts were designed for installation of reflectors in the nose and base of projectiles. Prior to the feasibility tests, a firing test demonstrated the integrity of the mounting technique.

In order to evaluate the nose mount configuration, the laser beam was reflected back into the muzzle with a folding mirror on the projectile path, 88 meters downrange. For evaluation of the base-mounted reflector, the folding mirror was placed about 15 cm to the side of the projectile path, with the beam crossing the path at 16 meters or further downrange.

The spin of the projectile is used to generate the angle information. The reflector assembly has a characteristic interference fringe angle that depends on the hologram diffraction angle and the retroreflector height and refractive index. Each 180° rotation modulates the reflected beam, where the number of modulation cycles is twice the angle between the beam and the spin axis divided by the reflector fringe angle.

Test results were positive for both mounting arrangements. The nose mount produces more information as the angle between projectile body axis and the beam is measured continuously from the muzzle to the folding mirror. The base mount generates data only when the projectile crosses the beam. In both cases the measurement resolution is better than 0.1°, but that wake turbulence may degrade the absolute accuracy of the base mount measurements.

Further work on this technology appears justified since the technique can be extended to obtain the complete angular position of the projectile. The demonstrated angle measurement system uses the zero-order beams from the holographic grating. Higher order beams are also available and these could be used to determine the transverse position of the projectile. In addition, the laser beam could be used as an optical radar to measure axial position.

II. INTRODUCTION

This document is the final report on contract DAAK11-83-C-0001. The results of this contract established the feasibility of measuring the yaw angle of a spinning projectile with the Boeing laser angle measurement system. The body of the report is a description of the test setup and test results followed by recommendations for further research. Preliminary design information for a measurement system based on the test results is included in the appendix.

III. TEST GEOMETRY

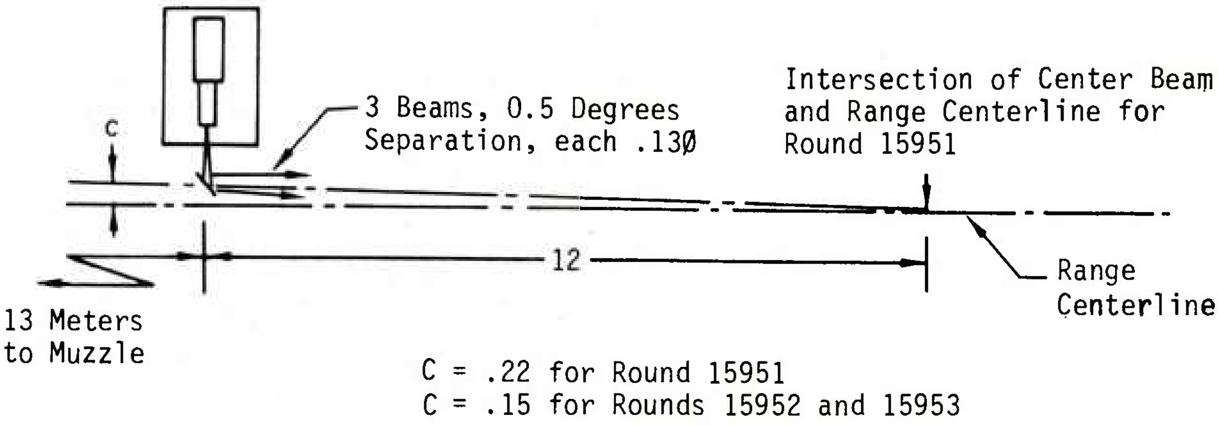
The two basic setups used during the test are shown in Figure 1. The best results were obtained with the arrangement shown in Figure 1-b, where the reflector assembly is mounted in the nose of the projectile and the projectile moves down the beam. The other arrangement (Figure 1-a) provides data only over a small part of the projectile path, since the beam is projected across the expected projectile path.

The laser optical system projects three beams in a horizontal plane. The beam diameters are 0.13 meters and the angle between adjacent beams is 0.5 degrees. The center beam crossed the projectile path as shown in Figure 1-a for round 15951 and good data were obtained. The beam was pointed to the expected impact point at the end of the range for rounds 15952 and 15953 in an attempt to get data through a long path in the projectile wake. Round 15952 passed through a beam at mid range, while round 15953 passed over all the beams.

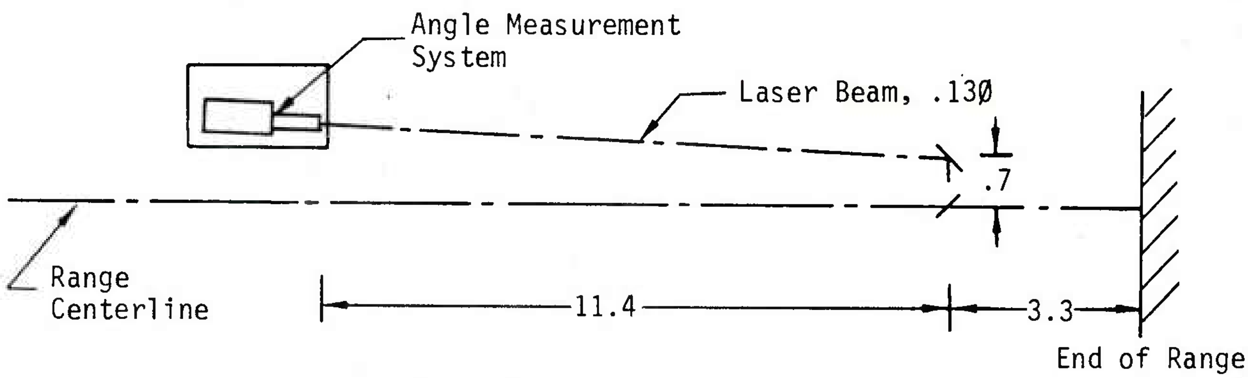
Rounds 15950, 15956, 15958, 15959, 15960, and 15961 were fired with the optical system at the end of the range, as shown in Figure 1-b. The central beam was pointed at the muzzle. Data were obtained on rounds 15950, 15956, and 15961.

Figure 2 illustrates reflector assembly details. The conical recess for round 15950 was drilled with a standard 120^{o} drill. All other nose mounts were drilled with a special drill that was ground to 109.5^{o}. The recess was filled with epoxy, then the cube corner retroreflector was pushed in with a wooden dowel, squeezing out excess resin. Care was taken to ensure that no air bubbles were trapped in the epoxy beneath the reflector. Two types of epoxy were used, Epo-Tek type 301 resin for the first four rounds and Epoxi-Patch type 615 for the last four rounds. The hologram disk was cemented to the retroreflector for the first four rounds. The disk was air spaced for the other four rounds, where the hologram disk was held in place with an epoxy fillet around the perimeter. All techniques were successful, but the Epoxi-Patch 615 is easier to use and sets in minutes without heat. The Epo-Tek 301 was cured in an oven at 60^{o}C for one hour.

Figure 3 is a block diagram describing how the data were recorded for reduction at a later date. An EMI SE7000M Wideband Tape Recorder was used for recording the data. The signal channels, channels 2 and 4, were recorded on wideband FM having a bandwidth from d.c. to 500 kHz. The timing signals, channels 7, 9, 11, and 13, were recorded on direct with a bandwidth from 400 Hz to MHz. Amplifiers, HP-465A's, were used between the photomultiplier outputs and the input to the tape recorder. The amplifiers provided the gain needed to adequately drive the tape recorder and were capable of driving approximately 100 meters of coaxial cable terminated with its characteristic impedance. The HP465A has a bandwidth from 5 Hz to 1 MHz. The photomultiplier load resistance was one kilohm. A Nicolet Instrument Corporation Explorer III digital oscilloscope, furnished and operated by BRL Aerodynamics Range personnel, was used to provide a quick coarse look at the data. The oscilloscope data was also stored on floppy diskettes. All recording of data on tape was done at 120 inches/sec.



a. Laser Beams Pointing Down-Range, Base Mount



b. Laser Beam Pointing Up-Range, Nose Mount

Figure 1. Test Setup at BRL Aerodynamics Range. Dimensions in Meters

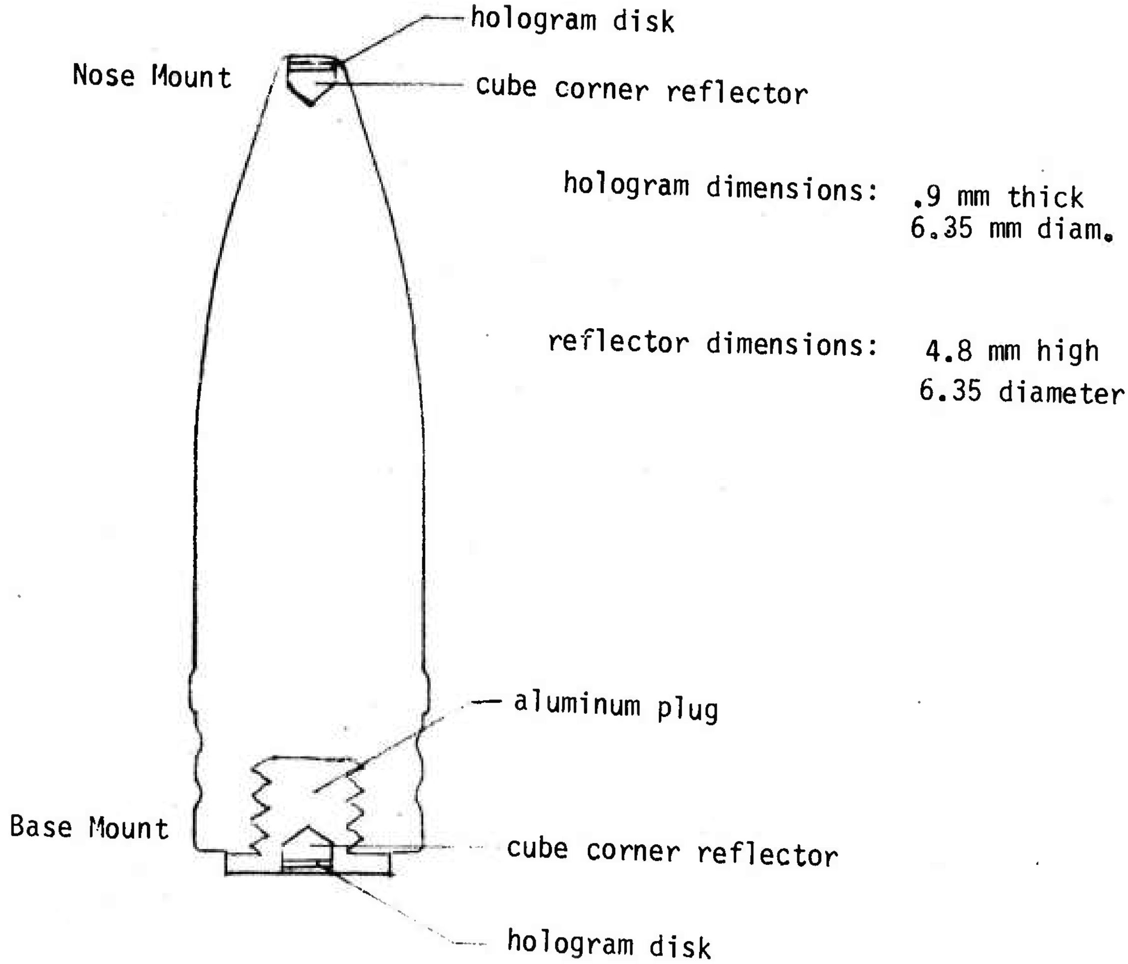


Figure 2. Reflector Assembly Mounting Methods

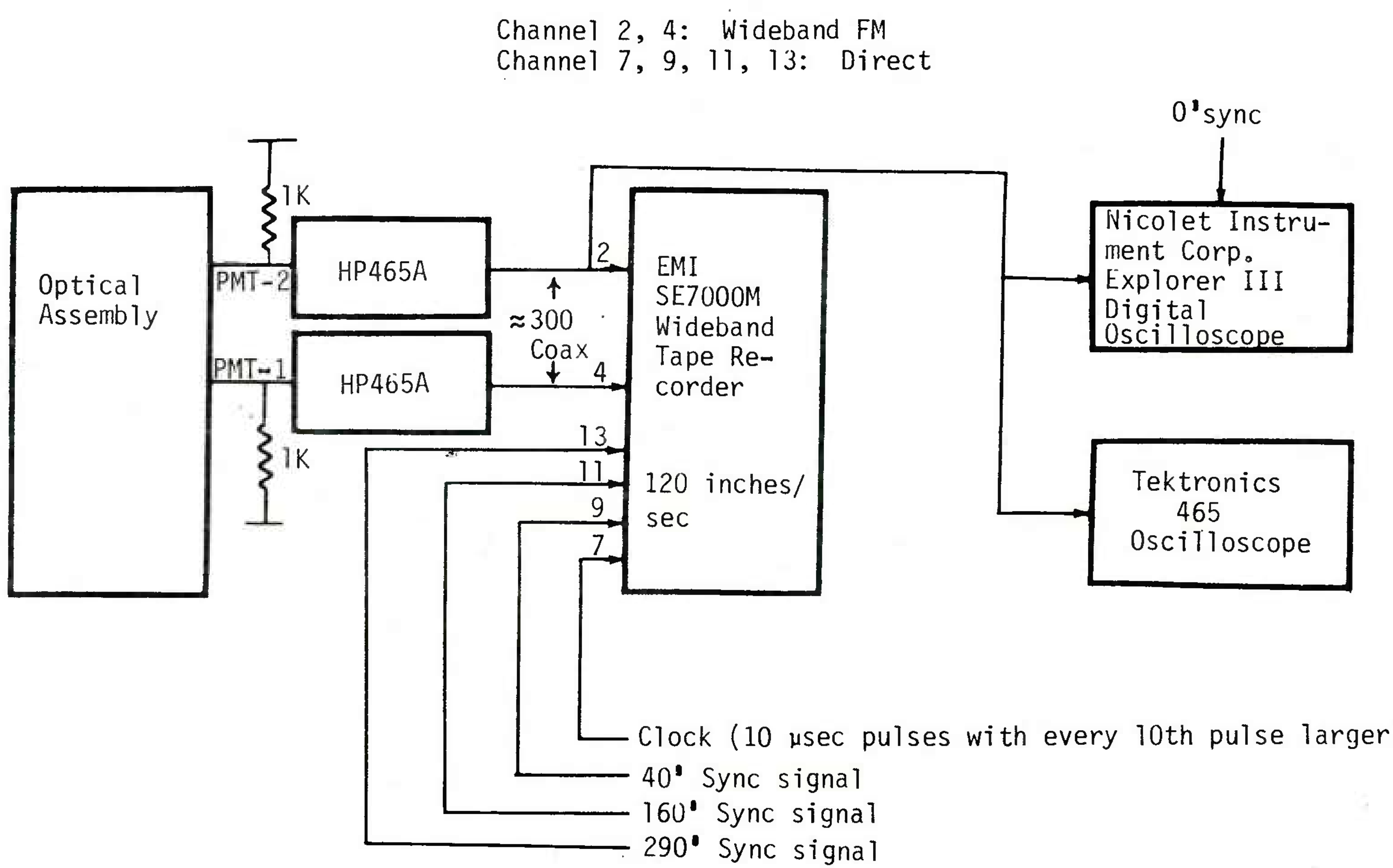


Figure 3. Diagram of Recording Instrumentation

IV. TEST RESULTS

A total of 11 rounds were fired during the test program. Eight rounds were fitted with reflector assemblies, 3 base mounts and 5 nose mounts. The reflector assembly characteristics are listed in Table 1. The hologram diffraction angles were measured during the fabrication. The fringe angles were calculated using the hologram and retroreflector specifications.

Table 1. Reflector Assembly Characteristics

Round	Reflector Position	Diffraction Angle	Fringe Angle	Comments
15950	Nose	0.5°	0.55°	Hologram emulsion on outside
15951	Base	0.5°	0.55°	"
15952	Base	1.0°	0.275°	"
15953	Base	2.0°	0.138°	"
15954	No reflector			Test round
15955	No reflector			Test round
15956	Nose	1.0°	0.275°	Hologram facing out
15957	No reflector			Test round
15958	No reflector			Test round
15959	Nose	2.0°	0.138°	Hologram facing out
15960	Nose	1.0°	0.335°	Hologram facing in
15961	Nose	2.0°	0.164°	Hologram facing in

Figure 4 is a block diagram of the data reduction instrumentation. A Honeywell 1858 visicorder with 1881 plug-ins was used to obtain a chart recording of the data signal, clock, and range marker as a function of time. The chart recording was used to manually analyze the data. The tape recorder playback speed was 1 7/8 inches/sec, 1/64 of the recording speed, and the visicorder was run at its maximum recording speed of 80 inches/sec. The resulting time resolution for the chart record was better than 10 microseconds.

The raw data is a frequency modulated signal, where one frequency modulation (FM) cycle occurs for each 180° rotation of the projectile relative to a plane containing the spin axis and the incident laser beam. The data reduction procedure is outlined below.

1) Determine end points of each FM cycle.
2) Count the number of fringes in each cycle to the nearest quarter fringe.
3) Muitiply the fringe count by one-half the fringe angle of the reflector assembly to get yaw angle.

Note that the resolution requirement of 0.1 degree is exceeded with a fringe count estimate to the nearest quarter fringe.

The reduced data were plotted by computer, where the calculated yaw angles versus time are connected with straight line segments dynamics. These angles are shown in Figures 5 through 9. Corresponding plots from the BRL Aero Range data system are shown in Figures 10 through 14. Agreement between the two data sets is excellent.

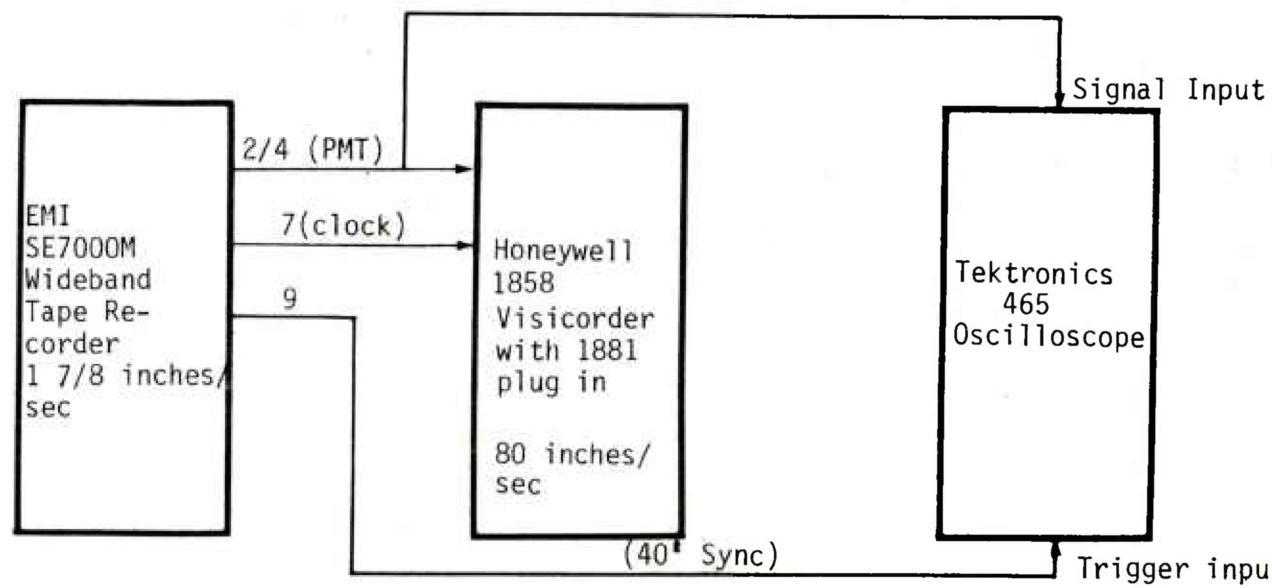


Figure 4. Diagram of Data Reduction Instrumentation

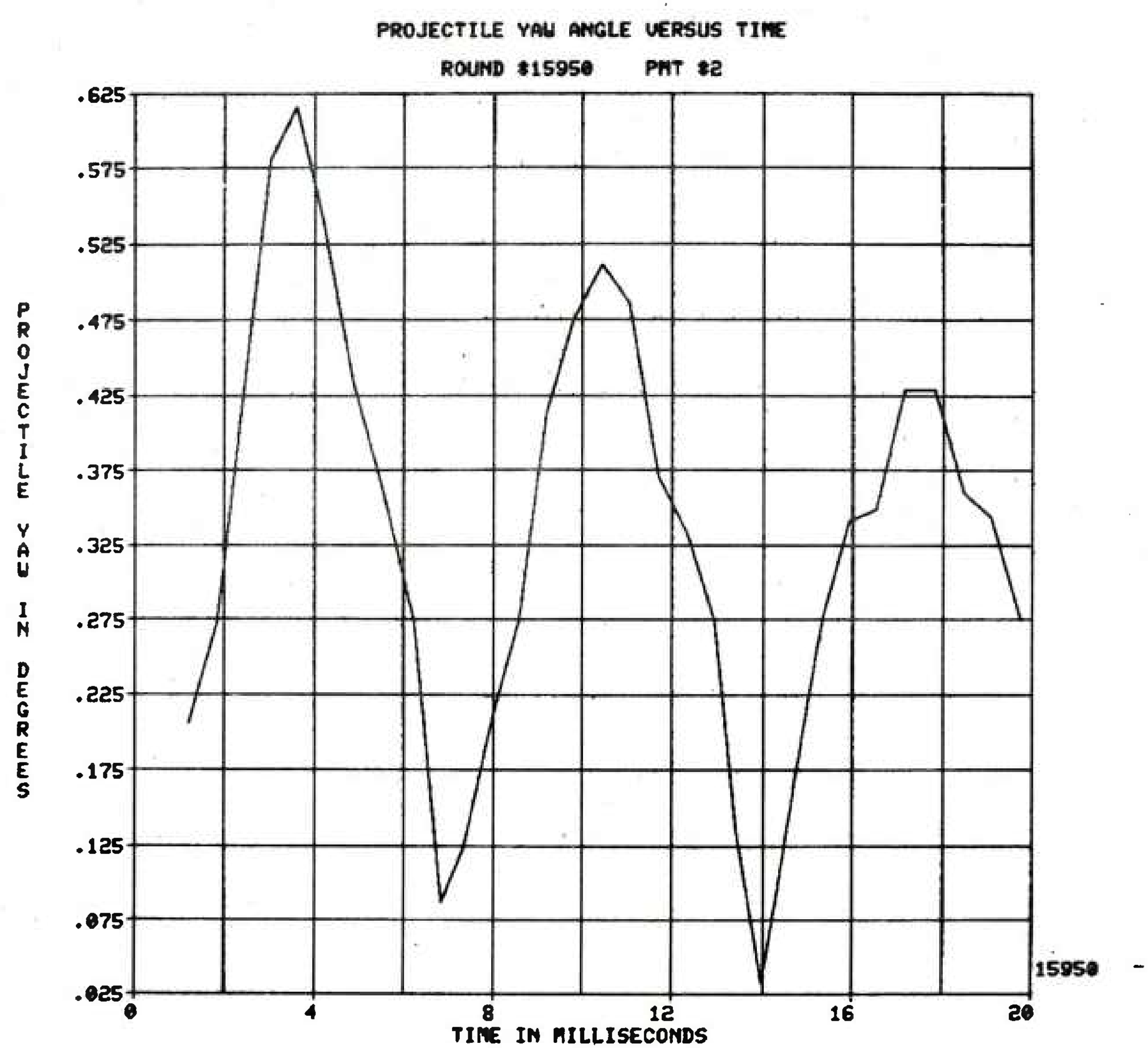


Figure 5. Projectile Yaw Angle versus Time, Round 15950

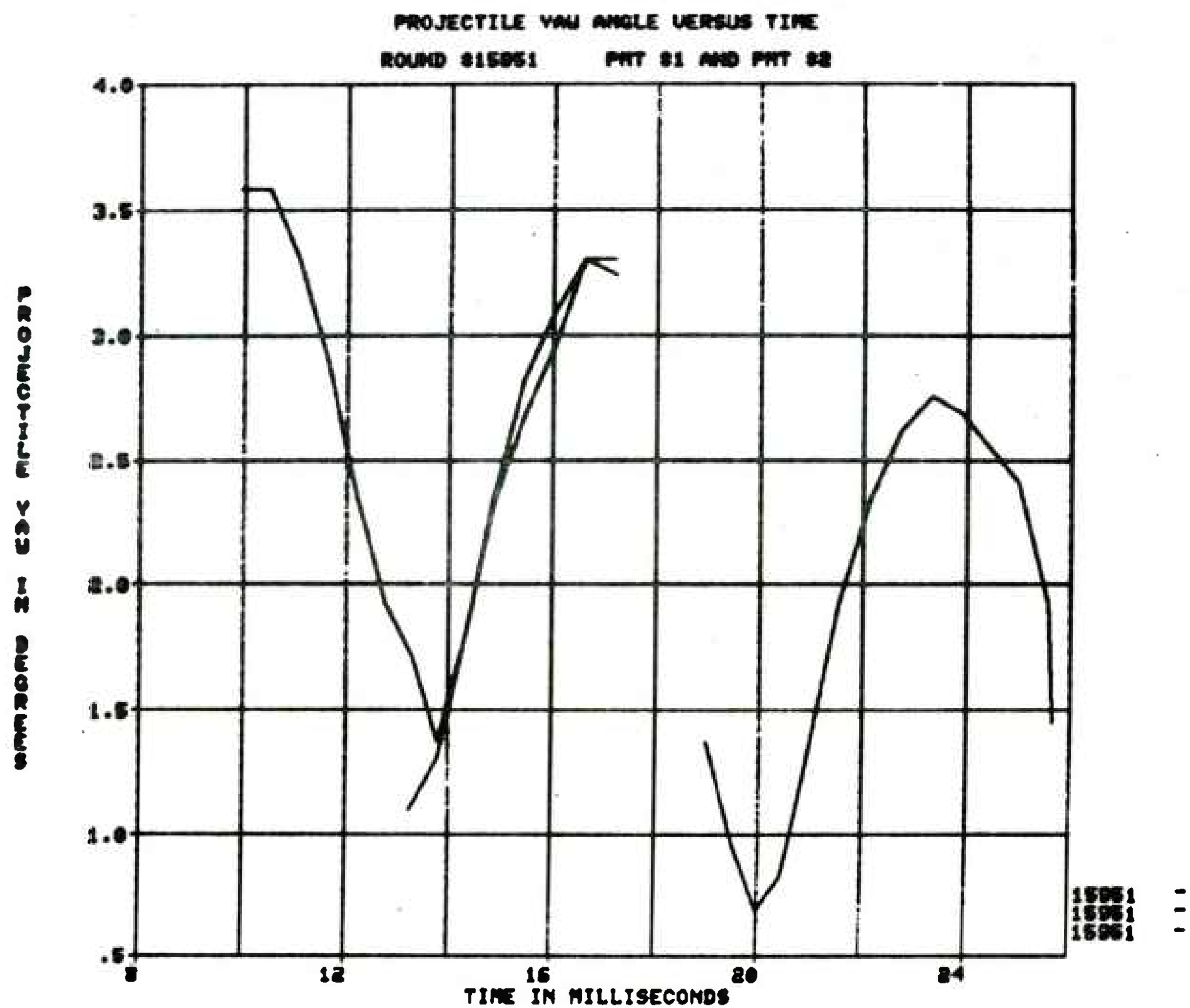


Figure 6. Projectile Yaw Angle versus Time, Round 15951

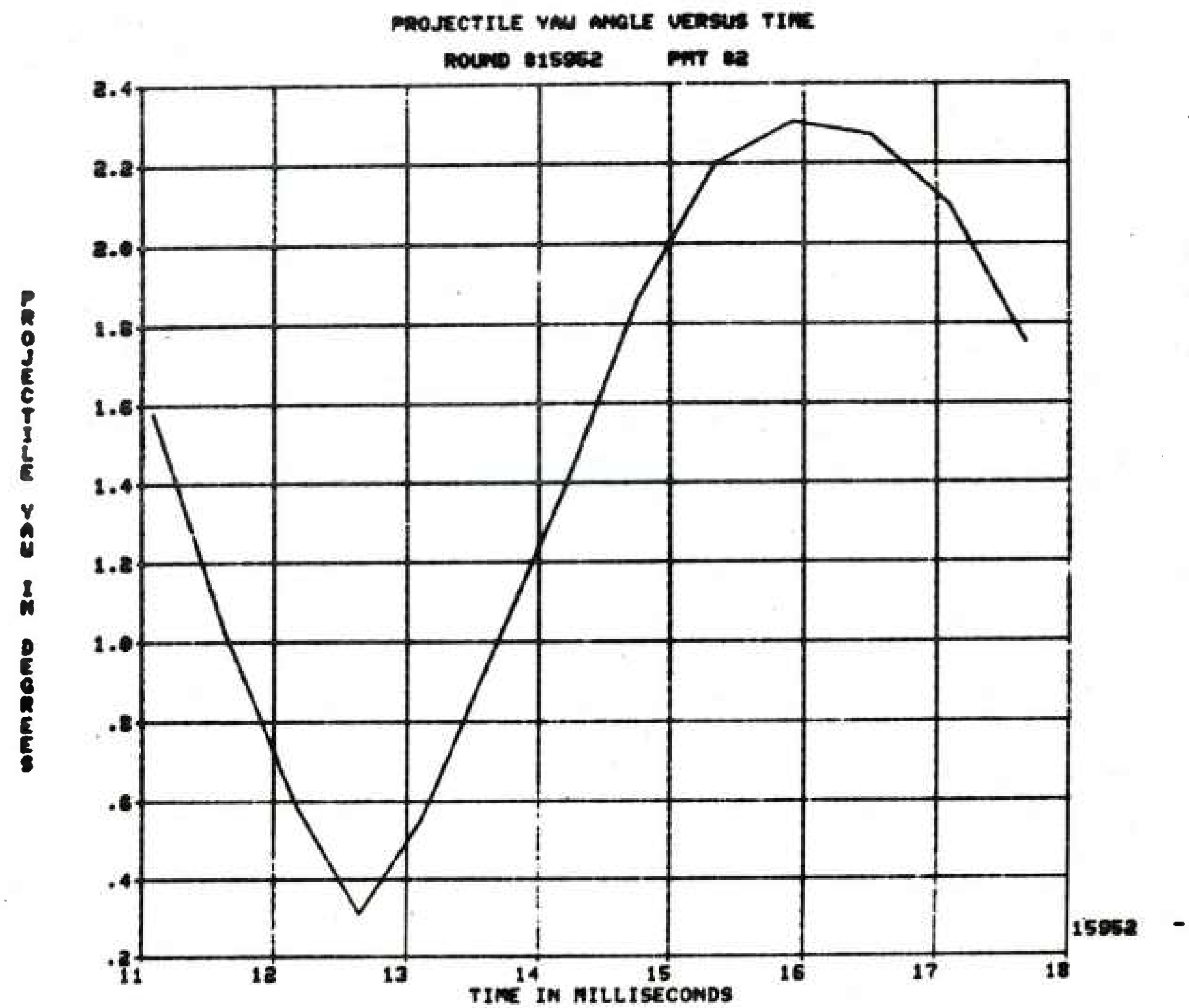


Figure 7. Projectile Yaw Angle versus Time, Round 15952

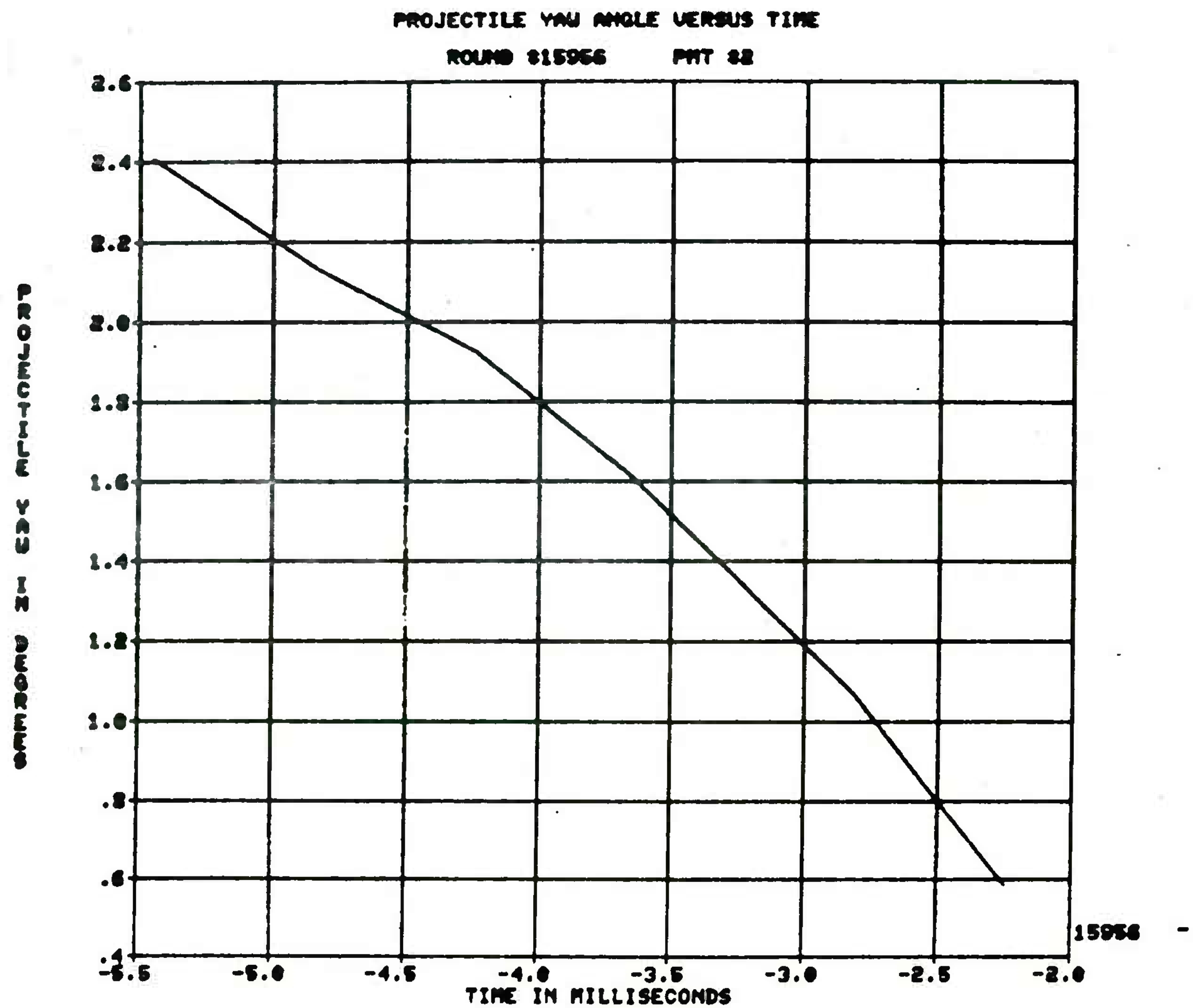


Figure 8. Projectile Yaw Angle versus Time, Round 15956

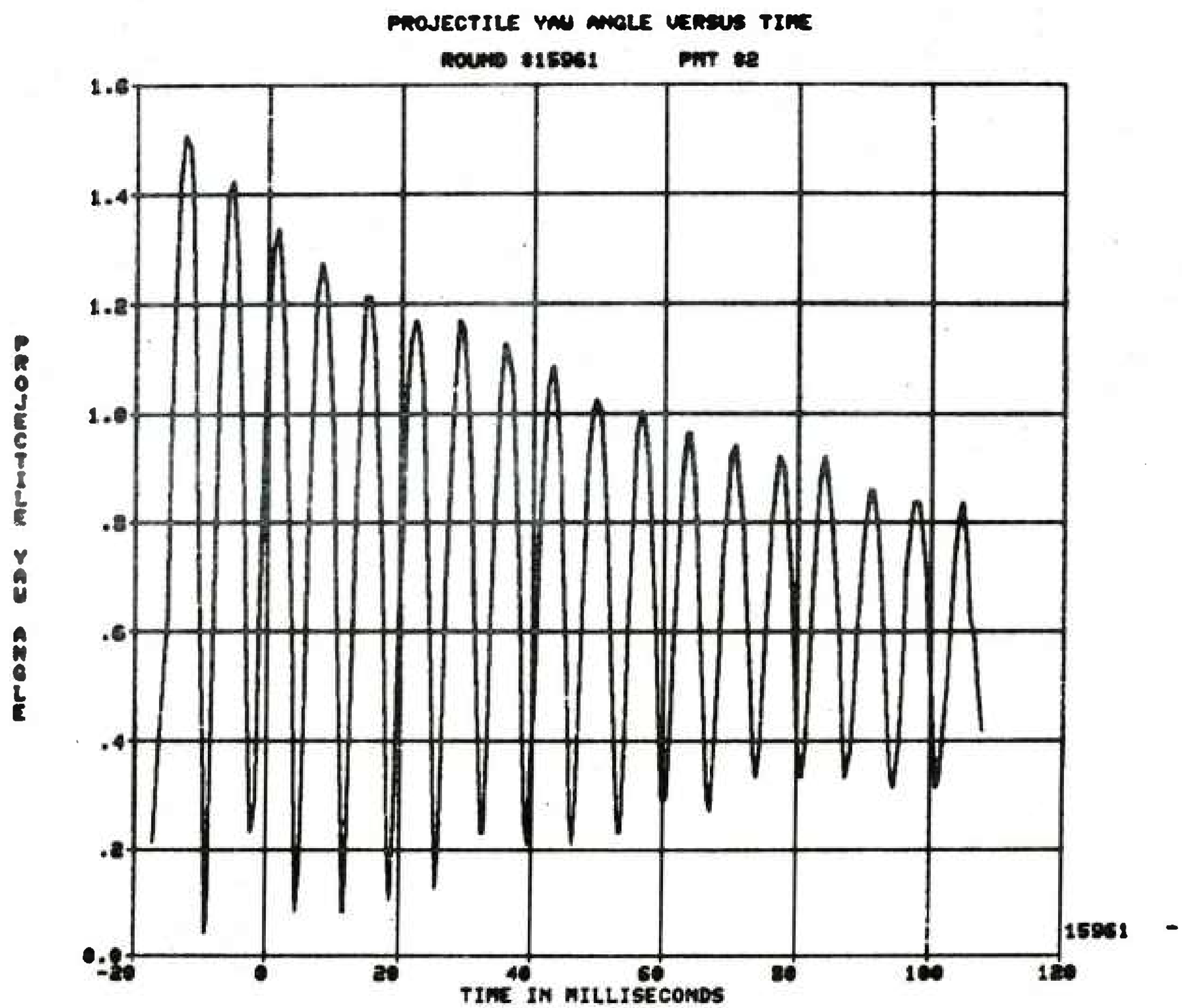
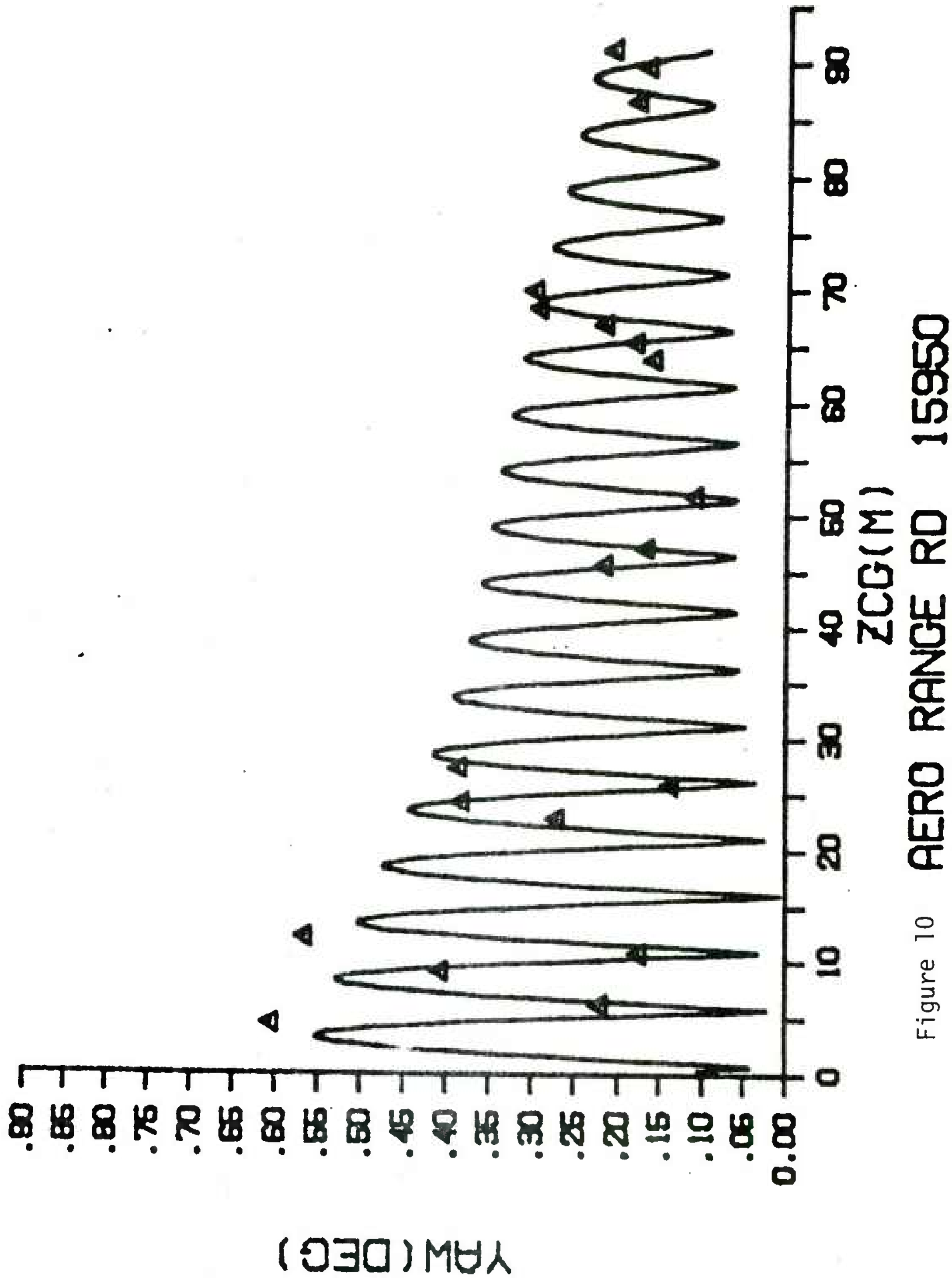


Figure 9. Projectile Yaw Angle versus Time, Round 15961.


YAW (DEG)
.90
.85
.80
.75
.70
.65
.60
.55
.50
.45
.40
.35
.30
.25
.20
.15
.10
.05
0.00
0
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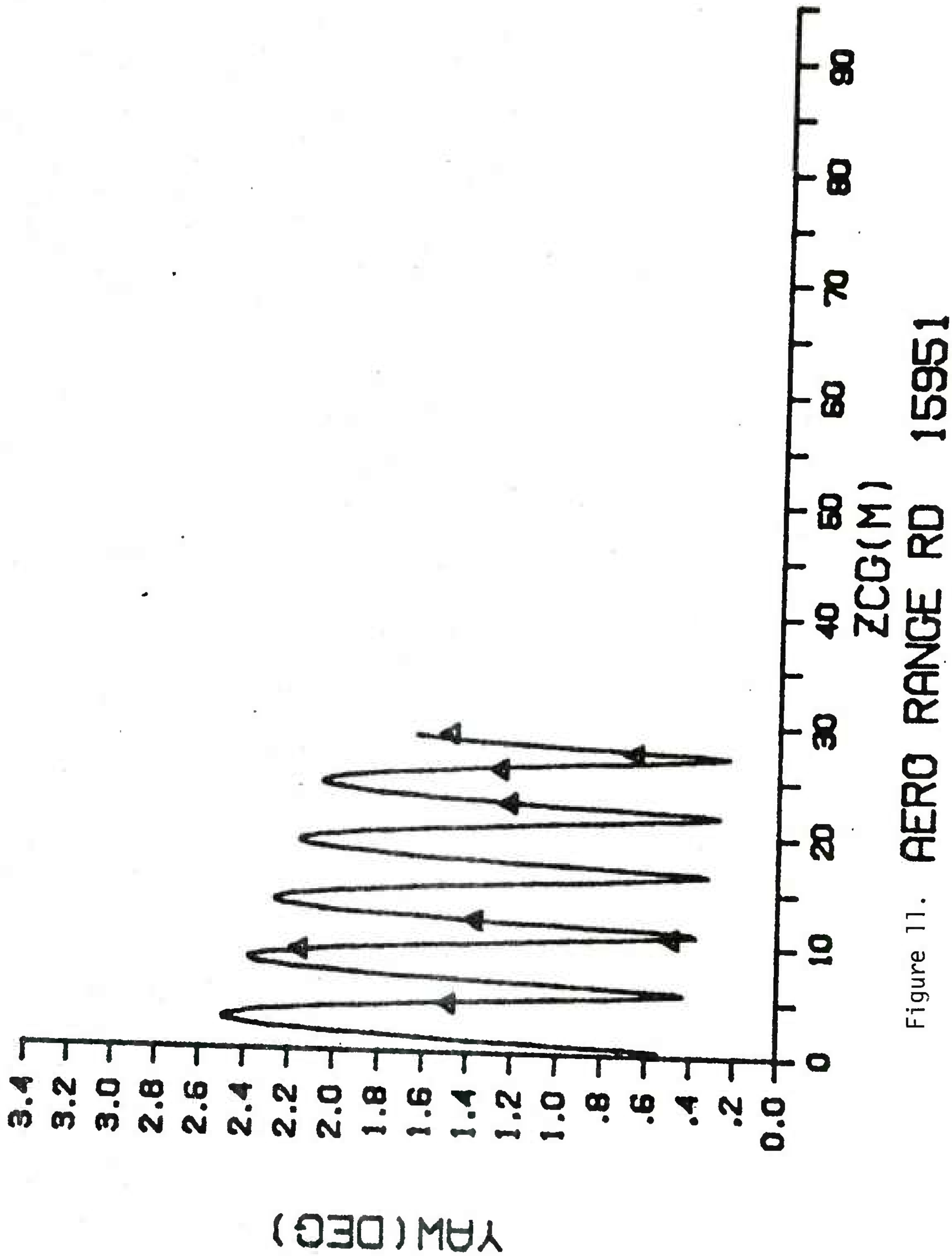
20
30
40
50
60
70
80
90
ZCG(M)
AERO RANGE RD 15950

Figure 10


YAW (DEG)
3.4
3.2
3.0
2.8
2.6
2.4
2.2
2.0
1.8
1.6
1.4
1.2
1.0
.8
.6
.4
.2
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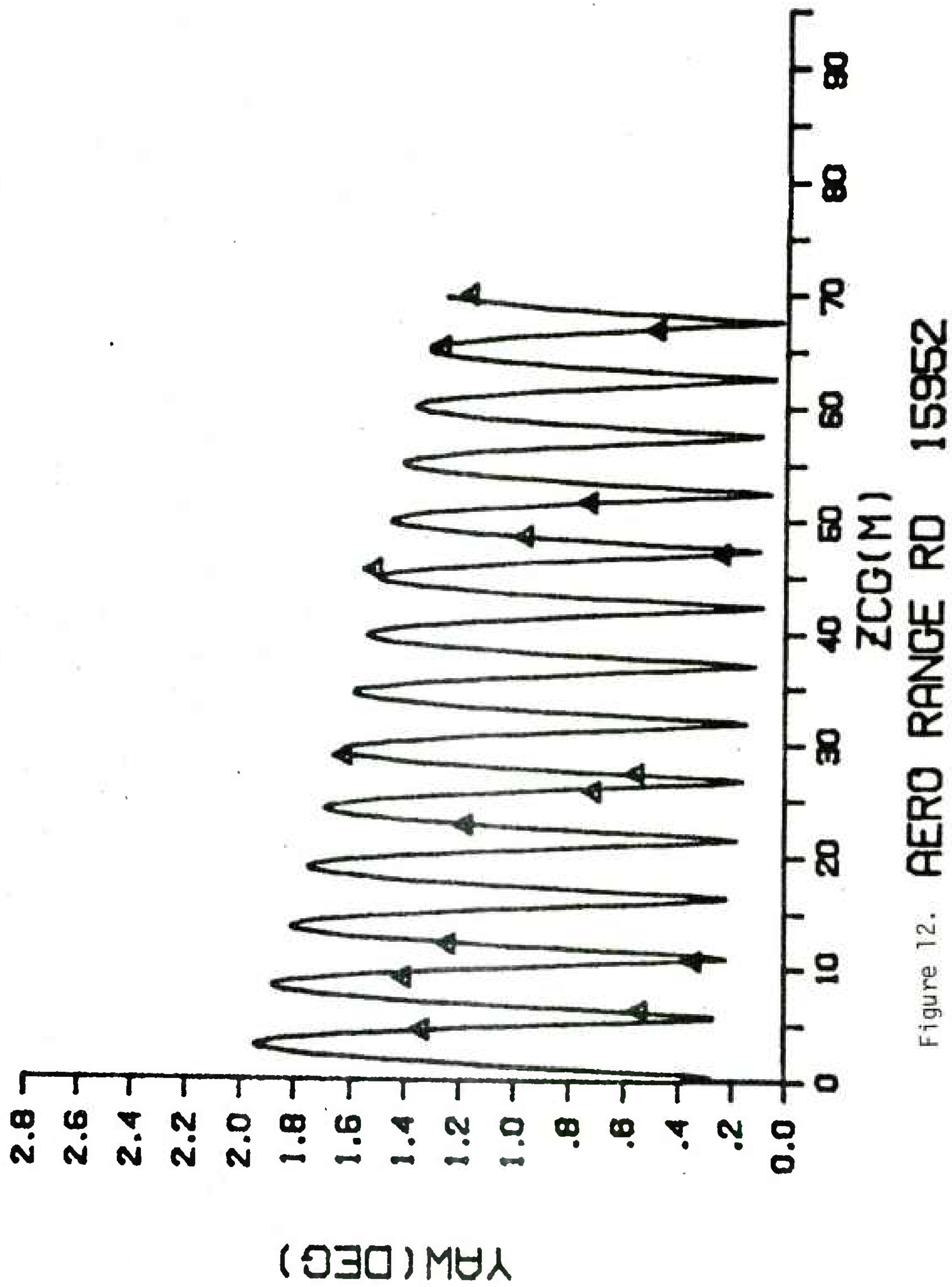
90
ZCG(M)
AERO RANGE RD 15951

Figure 11.


YAW (DEG)
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2.6
2.4
2.2
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ZCG(M)
AERO RANGE RD 15952

Figure 12.

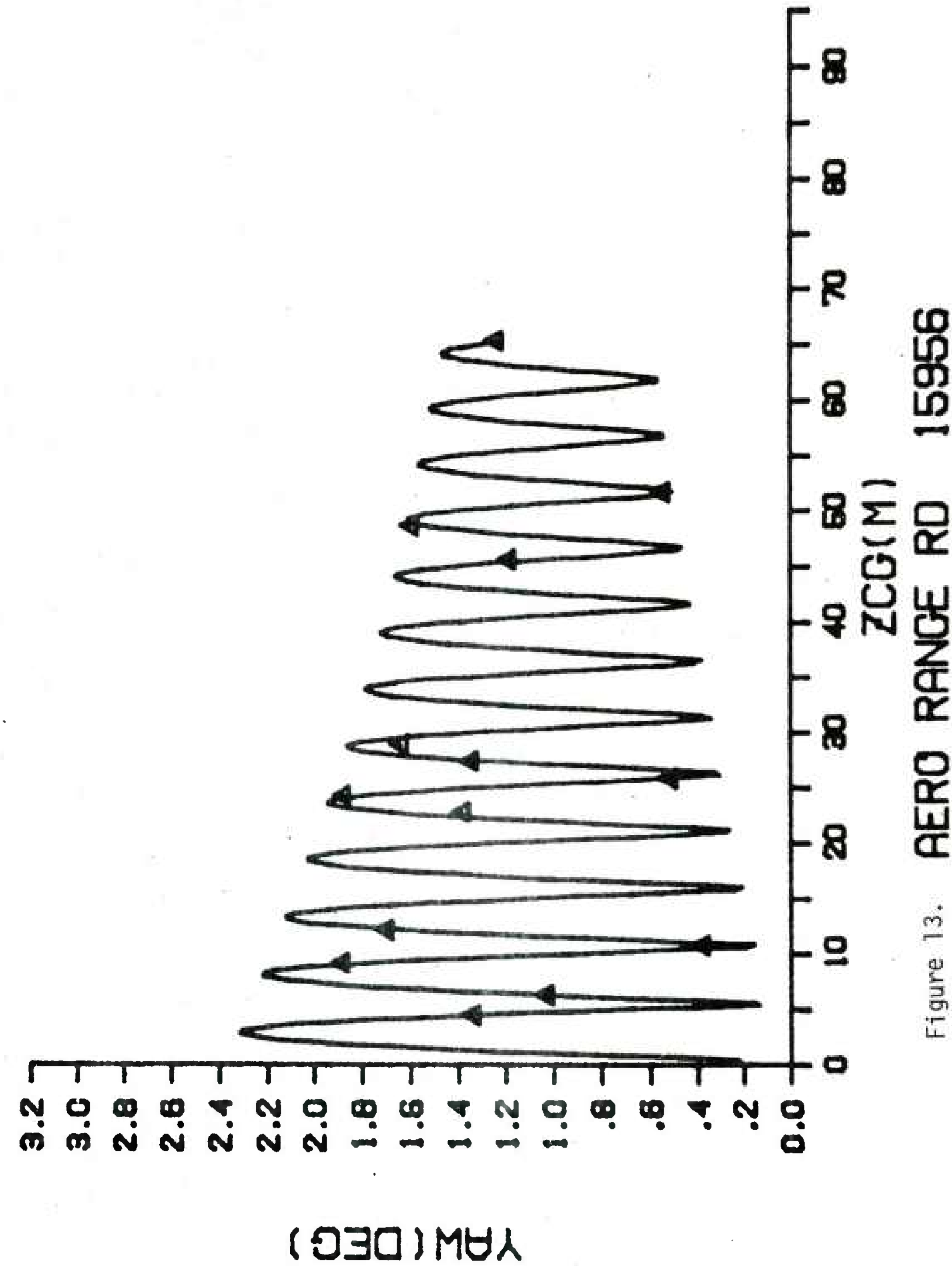
AERO RANGE RD 15956
ZCG(M)
YAW(DEG)
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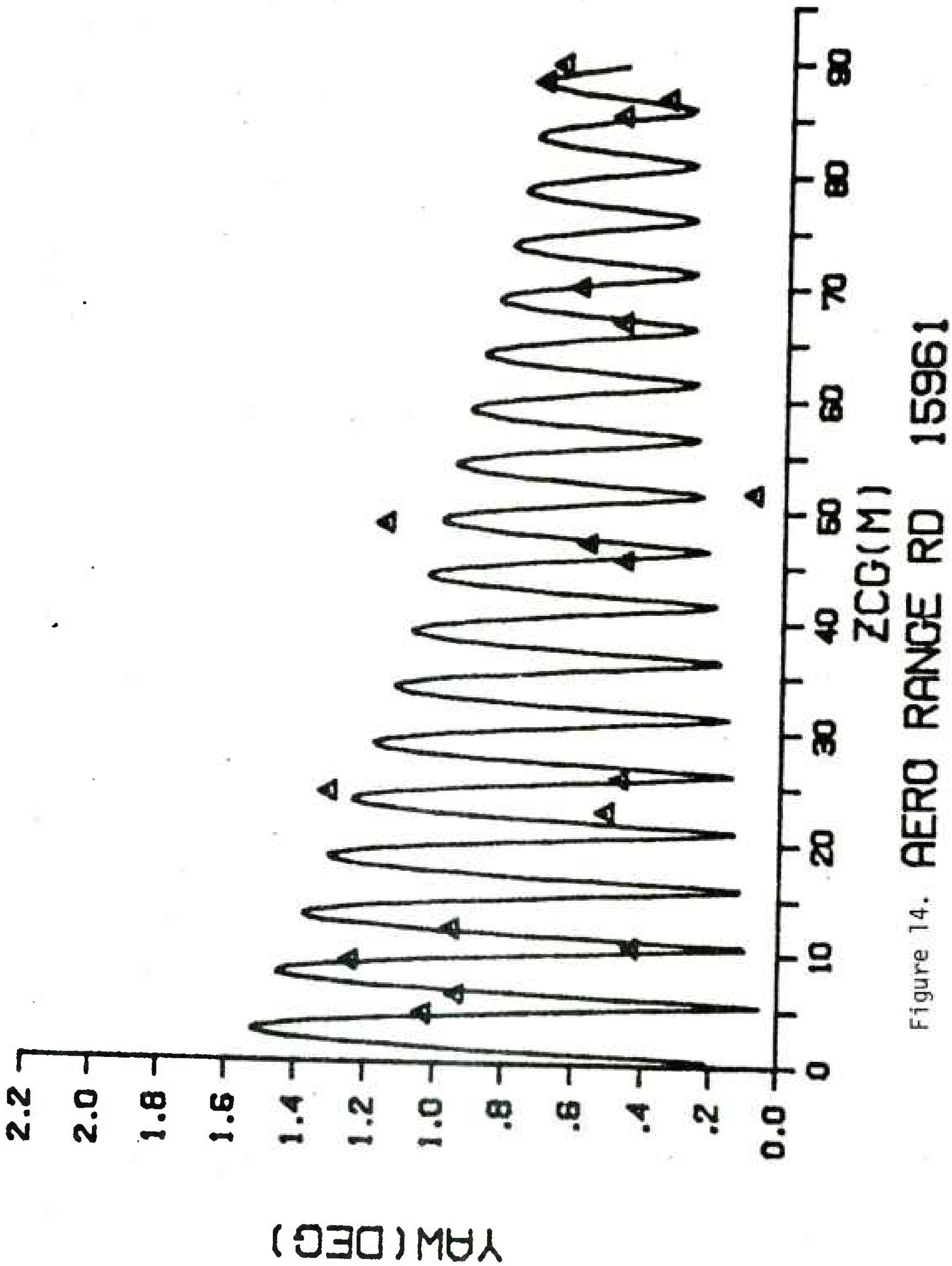
Figure 13.


YAW (DEG)
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ZCG(M)
AERO RANGE RD 15961

Figure 14.

V. CONCLUSIONS AND RECOMMENDATIONS

The major results and conclusions of this test program are the following:

(1) The Boeing angle measurement technique can be adapted to projectile angle measurement.
(2) A simple and effective reflector mounting method was devised and tested.
(3) The measurements indicate that aerodynamic heating is a problem when the hologram emulsion faces out, but nose-mounted reflectors with the emulsion facing the reflector survive over the length of the Aerodynamic Range (91 meters).
(4) The optical equipment can be set up and aligned quickly. The equipment was unpacked and set up at the test site in one day.
(5) The technique provides high resolution measurements. On round 15961, a fringe count resolution of 1/4 fringe corresponds to 0.02° angle resolution.
(6) The signal-to-noise ratio was adequate with a 13 cm beam illuminating a 6 mm reflector at a distance of greater than 100 meters. The shadowgraph spark illumination did not present an interference problem.

Additional research on the use of the Boeing laser angle measurement system for ballistic measurements is recommended. Some directions for this research are listed below.

(1) Develop an improvement to measure two angular coordinates of non-rotating projectiles.
(2) Investigate the feasibility of in-bore yaw angle measurement.
(3) Checkout the use of ± 1 and higher order beams for measuring the transverse position of the projectile.
(4) Evaluate the system for field measurement of the first maximum yaw angle.

The optical system used for the present program could be modified for any or all of these investigations.

ACKNOWLEDGMENTS

We would like to acknowledge the excellent support by the range personnel during this program. The technical results obtained were due in large part to the cooperation and assistance we received.

APPENDIX A

APPENDIX A

PRELIMINARY DESIGN

This appendix is a discussion of preliminary design concepts for a yaw angle measurement system. Because of the limited number of tests performed, however, we feel that additional research is necessary before committing to hardware development. The specifications and performance estimates in the following are based on demonstrated performance and results obtained in the test program.

Figure A-1 shows the essential elements of a yaw angle measurement system where the preliminary specifications are listed in Table A-1. The optical subsystem is a high quality collimator with a special transmit/receive (TR) switch that spatially filters the outgoing beam and transmits the zero-order return beam from the projectile. A low power helium-neon laser (~5 milliwatts) provides enough optical power for angle measurement and for visual alignment to the projectile path. The TR switch is a small (7 x 10 micron) mirror on glass oriented at Brewster's angle. The TR switch reflects a spatially filtered beam to the collimating lens and transmits more than 90% of the return beam. The collimating lens is a two-element lens of the variety used for astronomical telescopes. The folding mirror is adjustable in azimuth and elevation to facilitate centering the beam on the muzzle.

The reflector assembly is cemented into a recess at the nose of the projectile as described in the body of the report. The hologram emulsion faces inward toward the cube corner reflector because of aerodynamic heating that destroys an outward-facing hologram in 20 to 30 milliseconds of flight.

The arrangement shown in Figure A-1 provides the angle between the projectile spin axis and the beam direction as a function of time. Two systems, with beams that cross along the projectile path, could be used to determine azimuth and elevation components of the spin axis. The optical system could also be used with a base-mounted reflector assembly, where the folding mirror is near the projectile path and the beam crosses the path.

The expected performance of the system can be estimated from the measurements made in the test program. Measurement accuracy depends on beam alignment with the projectile path (including beam fluctuations due to atmospheric effects), calibration of the reflector assembly, and data reduction precision. In the test program we are able to align the beam at the muzzle to within ±3 cm at a range of 82 meters, for an angular accuracy of 0.021 degrees. We typically calibrate reflector assemblies in the lab to 0.01 degrees. The data reduction quantization error was a quarter-fringe, or 0.02 degrees for the highest resolution hologram tested. Considering these sources of error, an RMS angle accuracy of the order of 0.03 degrees can be expected.

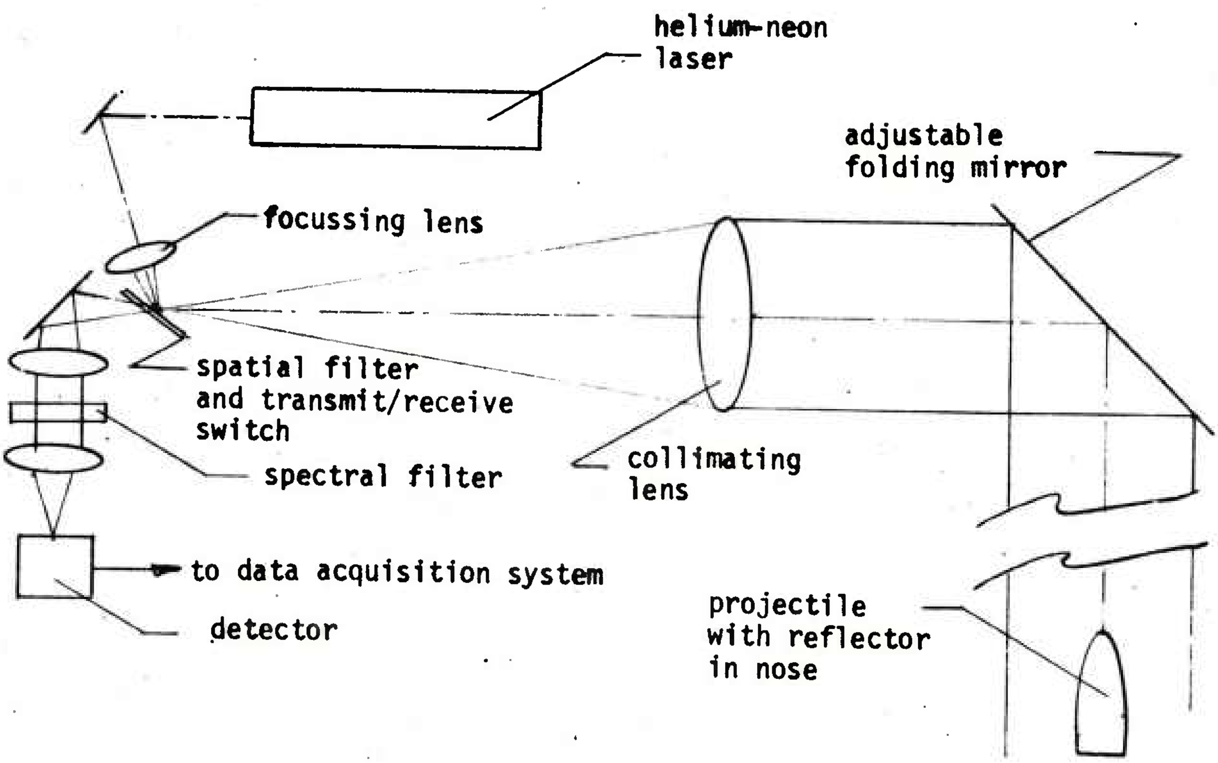

Figure A-1. Schematic of Yaw Angle Measurement System

Table A-1. Preliminary Specifications.

Laser	Helium-Neon, 633 nm wavelength 5 milliwatt, polarized, single mode
Focusing Lens	10X microscope objective
TR Switch	7 x 10 micron elliptical aluminum mirror on a 0.2 mm thick glass plate
Collimating Lens	15 cm clear aperture, F/5 doublet designed for infinite conjugate
Folding Mirror	First surface aluminized or gold-coated mirror, figure better than one-half wave/cm
Reflector Assembly	6 mm diameter cube corner reflector, BK-7A glass, bevel < 0.3 mm, height = 4.6 mm, return beam deviation < 1 arc minute, hologram on 1 mm glass, diffraction angle = 2 degrees, fringe angle = 0.16 degrees
Spectral Filter	3 nm bandwidth interference filter centered at 633 nm
Detector	S-20 photomultiplier

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