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MISS DISTANCE RADAR (MIDI) - A DEVELOPMENT FOR AIR DEFENSE WEAPONS TESTING

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Army Air Defense Board
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For many years the Department of Defense has sought ways and means of reducing the time frame and the cost of developing new weapons systems. Substantial savings can be made during the test and evaluation phases by improvements in instrumentation facilities and methods. The Miss Distance (MIDI) Radar is one example.

During the development of air defense weapons, both guns and guided missiles, the measurement of vector miss distance is necessary. This stems from the need to obtain detailed performance data on aiming, guidance, and fuzing subsystems during the development, testing, and technical evaluation phases. This has led to rather complex, sometimes redundant scoring devices. Historically, vector miss distance information has been collected by optical instrumentation which has the inherent limitations of: (1) Sophisticated test range facilities are required to support the effort, (2) Excessive time is required for the reduction and analysis of photographic data, (3) The rate of fire capability is considerably below that required for existing weapons, (4) Testing is limited to fair weather daylight hours, (5) Gun testing is limited to tracer ammunition only and, (6) Missiles must be large enough to permit photographic image recording at extended ranges.

Through the support of U.S. Army Test and Evaluation Command (TECOM) Instrumentation Development Program, U.S. Army Materiel Command (AMC), a modern miss distance measuring system is under development. The system embodies a ground-based radar system and effectively offsets the limitation of optical instrumentation shown in the preceding paragraph. The feasibility for the concept was developed by the U.S. Army Air Defense Board, demonstrated during 1970, and culminated in a series of live firing tests at Fort Bliss, Texas.

Beginning

15

Concept

The concept of the miss distance measuring system is based on well established radar principles. The required radar is a four-horn monopulse system capable of automatically tracking aerial targets with a high degree of precision.

Figure 1 depicts a normal test situation wherein the aerial target approaches an air defense site and will ultimately be fired upon by the weapon system under test. Throughout the engagement, the MIDI Radar continuously tracks the target. This is accomplished by standard amplitude-comparison monopulse techniques that will be described later, thus the antenna beam will always be centered on the target and any metal object such as a bullet or missile that approaches the target must enter the beam and be illuminated by the radar energy.

The radar range gate will also be centered about the target, kept in position by automatic range tracking circuits. Because of the relatively large radar echoes from the target, it is difficult to detect the much smaller echo from the projectile; therefore, a series of "slave" range gates are inserted in the radar receiver. These gates are positioned adjacent to the target gate, contain no target echo, and can be used to sense the projectile and measure its position in the beam. Figures 1 and 2 depict a gun projectile flight path through the series of range gates.

The MIDI Radar produces signals that are directly related to the azimuth and elevation angle offsets between the radar beam center and the projectile. It accomplishes this by applying the same amplitude-comparison monopulse techniques used to provide automatic target tracking.

Amplitude-Comparison Monopulse Techniques (1)

An amplitude-comparison monopulse feed system is designed to sense any lateral displacement of the target (echo) from the center of the focal plane. The antenna consists of a common aperture simultaneously excited by four offset feeds. Thus the beam can be considered as four separate gaussian beams. Figure 1 also depicts a cross section of the antenna beam. The beam is symmetrical so that when the echo is centered, energy falls equally on each of the four horns. However, if the target moves off axis, causing the echo to shift, there is an unbalance [illegible] energy in the four horns. The radar senses the target displacement by comparing the amplitude of the echo signals excited in each of the horns. The RF circuitry for a conventional four-horn square sums the output from quadrants I and IV, subtracts it from the sum of the output of II and III to sense any unbalance in the azimuth direction. It also subtracts the sum of outputs I and II from the sum of III and IV to sense any unbalance in the elevation direction.

The subtractor outputs, called difference signals, are zero when the target is on axis, increasing in amplitude with increasing displacement of the target from the center. The difference signals also change 180° in phase from one side of center to the other. The sum of all four horn outputs provides a reference signal to allow detector circuits to use the phase change of the difference signals to determine error direction sense. The phase detector produces the output voltage: $e = /\Sigma/ \ /\Delta/ \ \cos\Theta$

where e = angle error detector output voltage

$/\Sigma/$ = magnitude of the sum signal

$/\Delta/$ = magnitude of the difference signal

Θ = phase angle between the sum and difference signals.

In a pulsed tracking radar system, the angle error detector is bipolar video, that is, it is a video pulse with an amplitude proportional to the angle offset and a polarity (+ or -) corresponding to the direction of the error. This video is normally processed to give a D.C. error voltage used to drive servo amplifiers which drive the antenna pedestal and keep the target at the center of the horn.

The range gate is kept centered on the target by a closed loop tracker similar to the angle tracker, errors in centering the range gate on the target echo are sensed, error voltages generated, and circuits are provided to drive the gate in or out as required to keep the target centered.

Projectile Measurement

Projectile position measurement is accomplished in the same manner that tracking errors are measured; however, separate range gates are necessary. These gates are positioned as close as possible and are slaved to the target tracking gate so that as the aerial target moves in or out in range, the clucter of gates remains centered on the target. Difference signals are generated when a projectile passes through the slave gates. Again, the amplitude of these signals represents offset distance from the beam axis and polarity indicates the direction. These slave gate difference signals are extracted and processed by a digital mini-computer where the final miss distance computation is made. Photographs and recordings of the difference signals are shown in Figures 7, 8, and 9.

The position of the slave gates in the MIDI is adjustable, both can be positioned in front of the target gate, both behind the target gate or one on each side as shown in Figure 2.

A projectile describing a path through both slave gates can be located in gate S1, also located in gate S2. A straight line connecting point X1, Y1 with point X2, Y2 will pass the target in gate T. The point where the line approaches nearest to the target is the point from which miss distance will be computed.

When using the MIDI to score gun type weapons, it is possible to measure the miss distance by the use of a single slave gate. In this case, the two points used to describe the line are: (1) The space position of the slave gate (and the position of the X1, Y1 point in the gate) and (2) The ground location of the gun. In this case, the exterior ballistic data of the ammunition describes the line from gun to point in the gate.

When using the MIDI to score guided missiles, it is necessary to use two or more gates because a guided missile will attack the target from an unpredictable angle. The terminal maneuver will approximate a straight line over the 30 meters between the first and last gate, but the approach will be from any one of a group of approaches that are defined by classified missile performance characteristics. An interesting point is that the two slave gates must be in front of the target gate to score missiles with proximity fuses. When a fuse or warhead detonates from proximity to the target, the debris that will pass through a late gate appears as many targets and will not locate the necessary single point in the gate. This can be visualized by interchanging the position of target gate T1 and slave gate S2 in Figure 2.

Radar Performance Characteristics

To enable satisfactory miss distance measurement on existing weapons systems, the radar is required to have some characteristics that are unusual in the sense that they may not be required on the normal tracking radar.

1. The radar must have a very high range resolution capability. The simultaneous presence of more than one projectile in the slave gate destroys the ability to sense their individual off-axis position. Therefore, the gates must be more narrow than the bullet-to-bullet spacing of modern high rate of fire guns. A 30-nanosecond radar pulse width permits the range gate width of five meters. This

will meet the firing rate of 3600 rounds per minute achieved by the Army's Vulcan air defense gun. (See Figure 6.)

2. The spacing of the slave gate with respect to the target gate must be minimized. Target echoes from the aircraft or target missile must not appear in the slave gate. Also, a projectile or missile approaching the radar beam from a high angle of incidence must not be allowed to pass "between the gates" and avoid detection. The minimum gate spacing is again controlled by the radar pulse width. A rectangular 30-nanosecond pulse dictates that the minimum spacing between gates will be five meters; however, because the RF energy is not completely contained within a 30-nanosecond pulse, the minimum spacing has been increased to 10 meters.

3. The radar must be capable of dealing with target and projectiles in close proximity in the time domain. The smallest projectile will be a 20mm; the largest target will be a military aircraft. Estimates of the relative magnitude indicate a difference of 30 to 50 decibels. Thus the system must be capable of operating on very small projectiles in the near gate, large signals from the target gate 60 nanoseconds later, and must recover in the same time to respond to another small projectile in the far gate.

4. When operating with gun systems which have a limited engagement range, the radar must have sufficient energy to excite a very wide antenna pattern in order to accommodate large miss distances. When operating with missile systems, the antenna pattern must be narrow to provide the required energy at the greater engagement range.

5. Operating frequency in the 9 to 10 GHz region, where one wavelength equals approximately 30mm, has been selected to optimize the radar reflectivity of a 20mm projectile. Fortunately, this frequency also optimizes the performance of monopulse feed and comparator circuits. (2)

6. To obtain precision tracking and off-axis measurement, it is necessary to keep phase errors small in the radar receiver. These errors could cause shifts in boresight and loss of angle sensitivity. It is possible to design and build conventional monopulse comparators that are completely passive, symmetrical, and of short electrical path length. These features will keep phase errors small and will also contribute to deep, stable nulls at the center of the antenna axis. (1)

Because the projectile offsets measured in the antenna beam are one of the accuracy limits of the MIDI, it is necessary to implement a precision calibration of the antenna system. Under computer control, the antenna beam is swept past a pole-mounted radar reflector, in both azimuth and elevation angle while the offsets are precisely measured at 1 mil increments. The results of this calibration are stored for application during the miss distance computation.

Data Processing

The mini-computer provides a multiplicity of functions necessary to support the miss distance determination.

1. It must keep track of the space position of all three gates.

2. It must perform the comparative analysis of difference signals in all three gates since these signals describe the point within each gate that a target appears.

3. It must store and apply the antenna calibration polynomials.

4. It must compute target space position, correct for tracking errors, and drive plotting boards and display units.

5. It must determine the presence of multiple projectiles in the gates when this occurs.

6. It must make the final computation of vector miss distance and record these data.

Concept Development (2)

To develop and test the concept, a four-horn monopulse tracking radar was obtained from Army supply. This radar contained most of the performance characteristics required of the MIDI. The two characteristics that were not met were: (1) The antenna pattern was very narrow and, (2) The pulse width was excessively long. Therefore, wide misses could not be scored and only rates of fire up to 600 rounds per minute could be used. The Vulcan air defense weapon (20mm) was used to fire at both stationary and moving targets. The vector miss distance was determined by analyzing data from this radar and comparing these results with vector miss distance determined by sophisticated optical instrumentation.

The final results of this comparison for stationary targets are shown in Figure 3. Six rounds were fired. Slant range from gun to target was approximately 640 meters; slant range from radar to target was approximately 1150 meters. The RMS value of all differences = 0.79 meters.

Nine rounds were fired at a drone aerial target flying a crossing course to the gun under the following conditions, as shown in Figure 4. Slant range from gun to target was from 847 to 914 meters;

slant range from radar to target was from 1304 to 1376 meters. Target speed was 150 knots. The RMS value of all differences = 2.12 meters.

The differences quoted herein were developed after correcting for radar range tracking errors. The average differences without the corrections were 1.4 meters and 2.2 meters respectively for stationary and moving targets.

The difference between the static and dynamic accuracy is attributed primarily to tracking errors such as target glint, scintillation and lag errors. It appears that tracking errors define the maximum accuracy that can be achieved by this system. The errors encountered agree favorably with the predicted glint errors shown in Figure 5. The magnitude of these errors is within the tolerances of the required accuracy for MIDI; therefore, no additional effort has been made to reduce them. It should be noted, however, that the system can be adapted for beacon tracking with expected improvement in accuracy.

Rate of Fire Limitations

The Midi system provides an independent measure for the offset of every projectile that passes through the system of gates. In order to function properly, it is necessary that the MIDI resolve the signals from individual rounds in a burst. The resolving power is limited by the radar pulse length. Hence, to be resolvable, the projectiles must have a spacing in the direction radial from the radar greater than the radar pulse duration.

The mean spacing of projectiles is given by the ratio of the projectile speed to the rate of fire. Since the speed decreases rapidly and steadily as the projectiles move down range, the spacing between projectile decreases proportionately at a fixed rate of fire.

Figure 6 shows the round-to-round spacing between 20mm rounds fired at a 3600-round-per-minute rate. The spacing will decrease from 17 meters to 4.5 meters over a 1500-meter trajectory. To score at 1500 meters, the radar pulse must be 30 nanoseconds or less wide. This calculation assumes each round will have the same ballistic performance as all other rounds. On occasion, the ballistic variance between rounds will cause more than one projectile to be in the slave gate concurrently. When this occurs, the MIDI will note the occurrence and miss distance data will not be computed for these specific rounds. The number of radar samples obtainable while the projectile is within a 30-nanosecond gate varies with projectile velocity and is shown in Figure 6.

Figures 7 and 8 are photographs of radar sum and difference video taken from "A" scope presentations during the firing tests. Projectiles fired were 20mm. The top sweep in both photographs shows the sum video. The bottom sweep shows the difference video in azimuth. Figure 7, showing positive offset, was taken when the slant range to the gate was 1860 meters. Figure 8 showing negative offset was taken when the slant range to the gate was 2835 meters. (2)

Figure 9 is a copy of an oscillograph recording made during these tests. A three-round burst of 20mm ammunition was fired at approximately 600 rounds per minute. This rate of fire was achieved by placing three dummy rounds between each live round and firing the weapon at 2000 rounds per minute. The recording clearly shows the angular offsets (Δ voltages) in the near and far gates as the projectiles pass. The angle at which the projectiles cross the radar beam is evident in the slope of the lines while the projectiles are gated. (2)

Conclusions

New Capabilities in Gun and Ammunition Testing

1. Projectile Dispersion Patterns. High rate of fire guns throw up a screen of lead much like a shot pattern of a shotgun except that the pattern is three-dimensional. These patterns will change with muzzle clamps, tracking rates, accelerations, and ammunition characteristics. Measurement of projectile-in-space patterns, difficult if not impossible to measure by other techniques, is readily available from the MIDI system.

2. Simulated Courses. The MIDI system will accept and track theoretical targets generated by simulators. The simulator is a device built to exercise a gun system by injecting theoretical target flights into the gun system to provide tracking experience to a gunner or to monitor the tracking performance of the gun. Therefore, if the gunner is tracking and firing on a theoretical target, and the MIDI is tracking and scoring on the same theoretical target, it becomes possible to test guns in their primary role--point defense.*

* An aerial target flying on an incoming radial course could, in the event of a hit, impact on a weapon system and injure the crew; therefore, for safety reasons, very few firing tests are conducted in this role even though it is the primary role of an air defense gun system.

FRENCH

Time and Facilities Conservation

The anticipated improvements in shortening the R&D cycle for new air defense guns and missiles are based primarily on the near real time capability of the MIDI as compared to the lengthy data reduction time required when using optical instrumentation. At the present time an estimated one to ten minutes is required to process all the data gathered in a burst of 100 rounds. This figure compares with several weeks that are required for reduction of optical data. Many thousands of rounds are usually fired during the development and testing of gun systems; therefore, the time savings can be appreciable. During the development of MIDI, some additional improvements in test capability became apparent. These improvements are listed and compared to the instrumentation and data reduction facilities used in the engineering and service tests of the Vulcan air defense system.

MIDI PERFORMANCE
20mm Weapons

Function	Optics	MIDI
Rate of Fire	600 RPM	3600 RPM
Scoring Radius	30 meters	50 meters
Accuracy	1-3 meters	0.7 - 3.5meters
Ammunition	Tracer	All Types
Data Availability	Months	Minutes
Man Hours Effort for One Minute of Data	200 Man Hours	2 Man Hours
Operating Personnel	40	2
Equipment Requirements	4-Cinetheodolites 3-Optical Trk Mts 1-Instr Radar 4-Film Readers 1-ADPE Facility	1-MIDI

REFERENCES

(1) Skolnick, M.I., Radar Handbook, Chapter 21. New York: McGraw-Hill, 1972.

(2) Final Engineering Report, Nike Hercules MDI, U.S. Army Air Defense Board, Fort Bliss, Texas, 4 December 1970.

(3) Skolnick, M.I., Radar Handbook, Chapter 28. New York: McGraw-Hill, 1972.

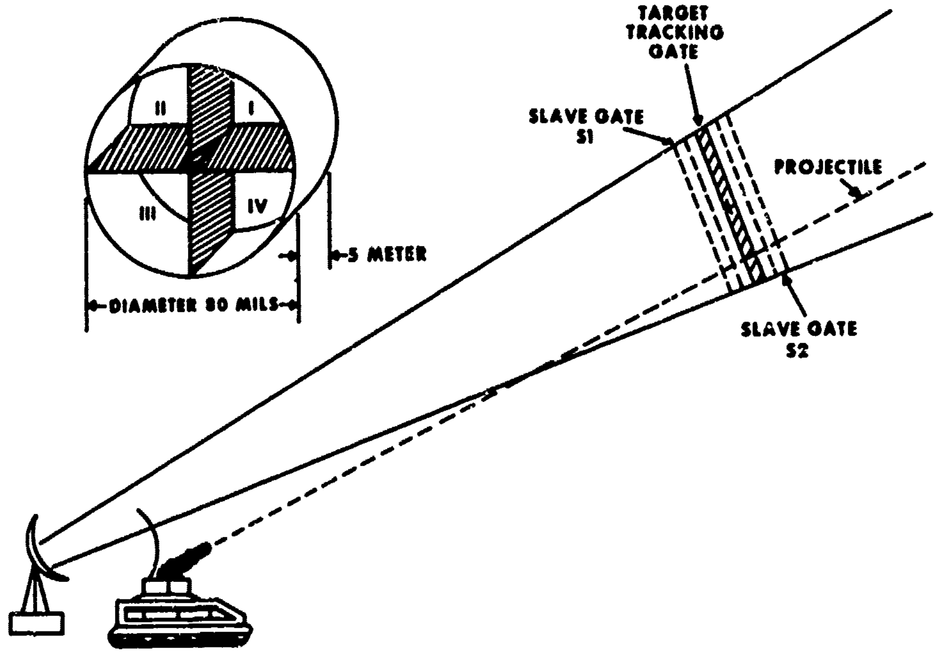


FIGURE 1.

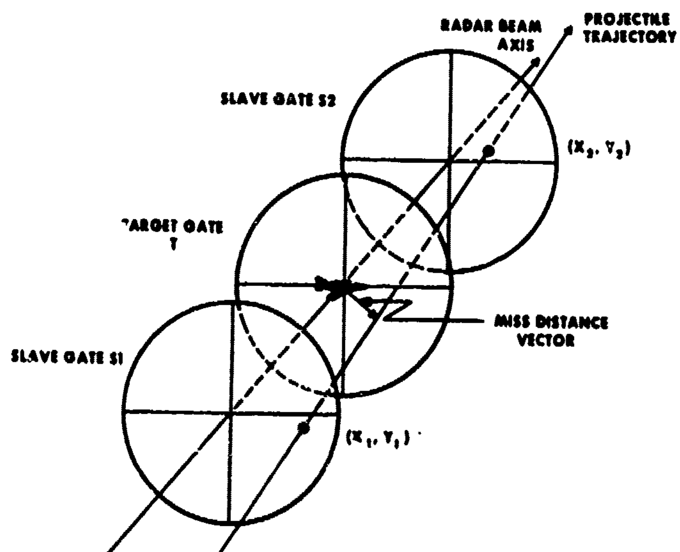
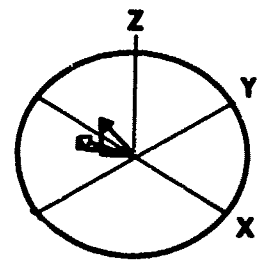
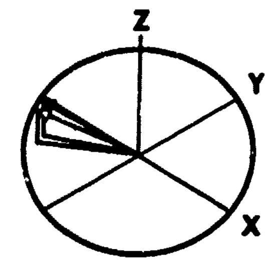


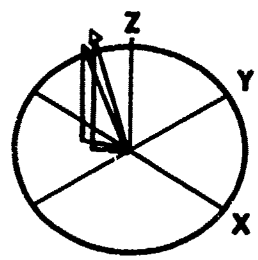
FIGURE 2.

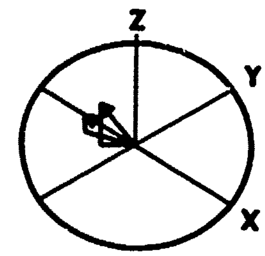




	X	Y	Z	MAG
MDI	−0.86	−0.48	1.06	1.44
THEODOLITE	−1.8	−0.5	0.1	1.87
DIFFERENCE				1.35

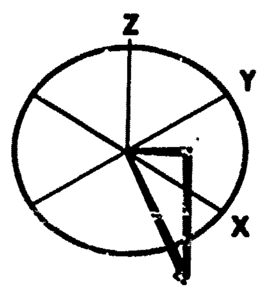
X	Y	Z	MAG
−3.98	−1.40	1.27	4.40
−4.1	−1.5	1.0	4.48
			0.31

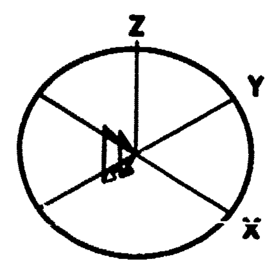




	X	Y	Z	MAG
MDI	−1.49	−1.47	4.36	4.84
THEODOLITE	−1.0	−1.5	4.7	5.03
DIFFERENCE				0.60

X	Y	Z	MAG
−0.81	−0.45	1.09	1.43
−1.5	−0.5	0.5	1.66
			0.91



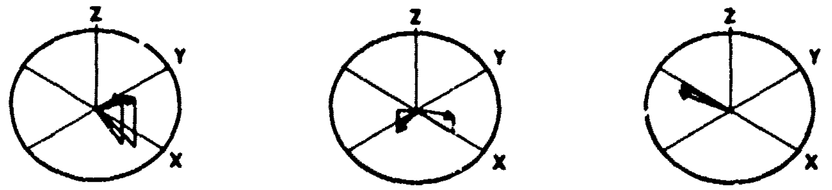


	X	Y	Z	MAG
MDI	2.37	1.45	−3.95	4.83
THEODOLITE	2.2	1.5	−4.1	4.89
DIFFERENCE				0.23

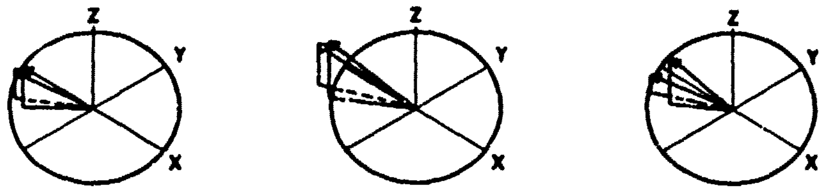
X	Y	Z	MAG
−0.73	0.22	−1.56	1.74
−1.4	0.2	−1.9	2.37
			0.75

MDI ⟶ THEODOLITES ⟶

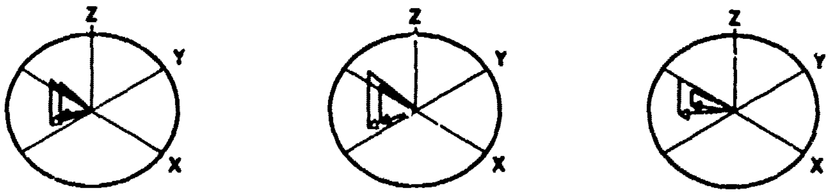
FIGURE 3.



	X	Y	Z	MAG	X	Y	Z	MAG	X	Y	Z	MAG
MDI	2.32	−0.64	2.24	3.29	2.70	0.05	0.63	2.77	−4.73	−0.59	0.30	4.78
THEODOLITE	1.8	−0.7	1.9	2.71	−0.6	0.6	−1.7	1.9	−5.7	−0.3	−0.30	5.72
DIFFERENCE				0.63				4.07				1.17



	X	Y	Z	MAG	X	Y	Z	MAG	X	Y	Z	MAG
MDI	−7.80	−2.94	3.38	8.99	−9.39	−4.08	5.62	11.70	−7.74	−2.73	3.28	8.84
THEODOLITE	−8.9	−2.6	2.3	9.55	−10.7	−3.6	4.6	12.19	−9.8	−2.2	1.4	10.14
DIFFERENCE				1.58				1.76				2.89



	X	Y	Z	MAG	X	Y	Z	MAG	X	Y	Z	MAG
MDI	2 92	0.70	−2.32	3.74	−5.06	0.33	−4.1	6.55	−4.17	−0.50	−0.54	4.23
THEODOLITE	−3 2	0.4	−2.6	4.14	−6.4	0.9	−5.4	8.42	−5.7	−0.1	−2.0	6.04
DIFFERENCE				0.41				1.87				2.15

MDI —→ THEODOLITES —▷

FIGURE 4.

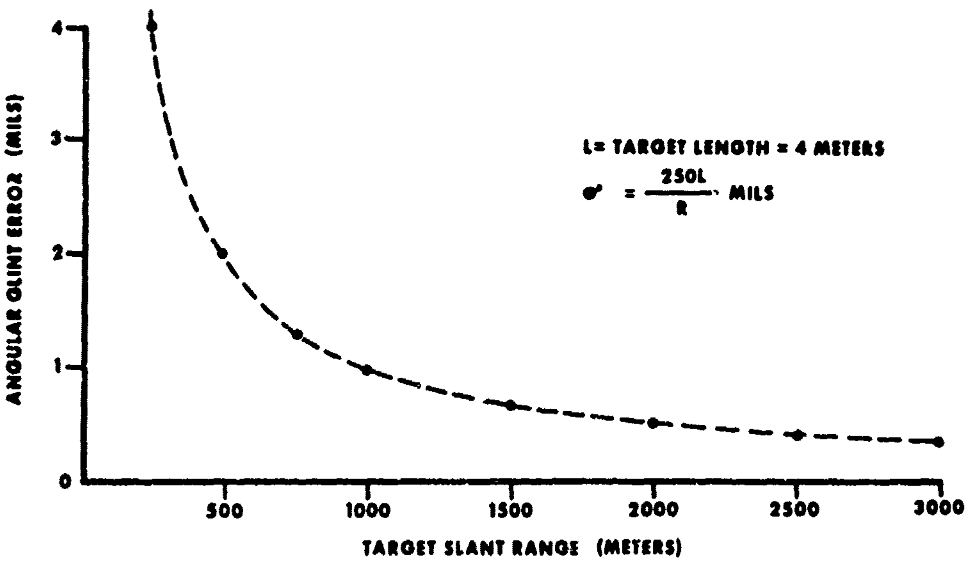


FIGURE 5.

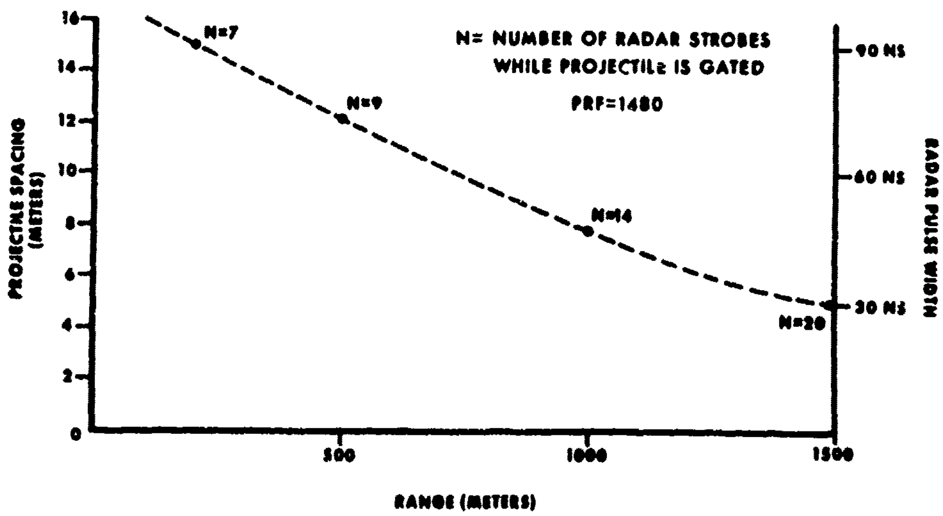


FIGURE 6.

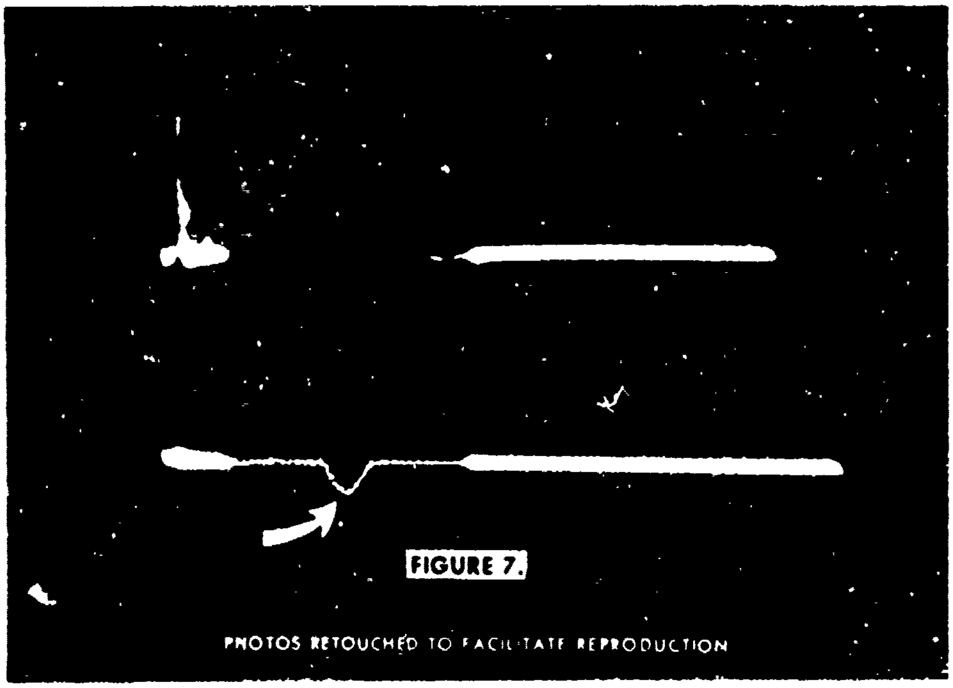


FIGURE 7.

PHOTOS RETOUCHED TO FACILITATE REPRODUCTION

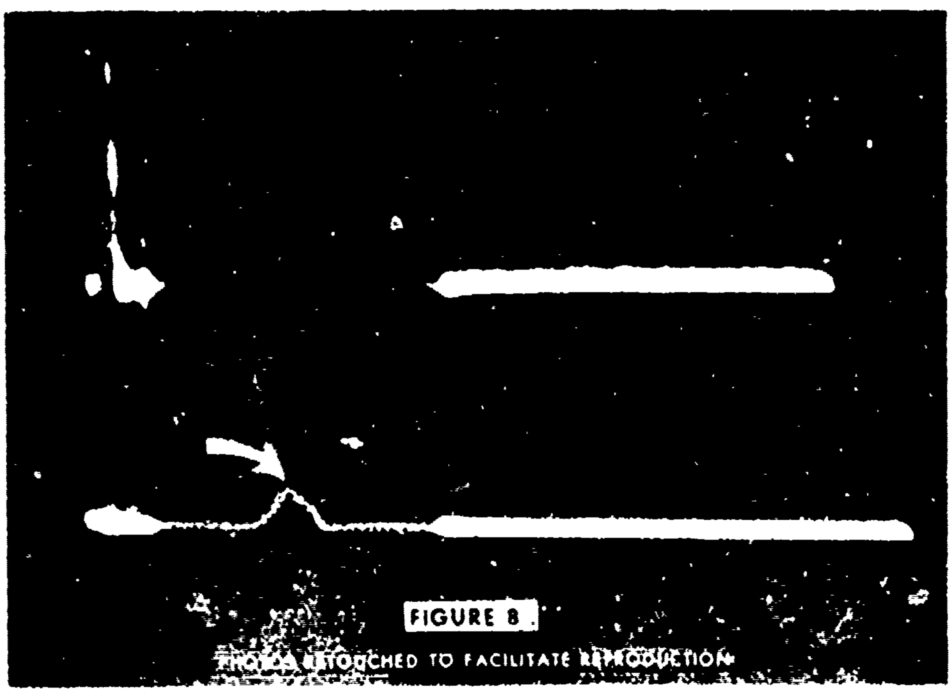


FIGURE 8.

PHOTOS RETOUCHED TO FACILITATE REPRODUCTION

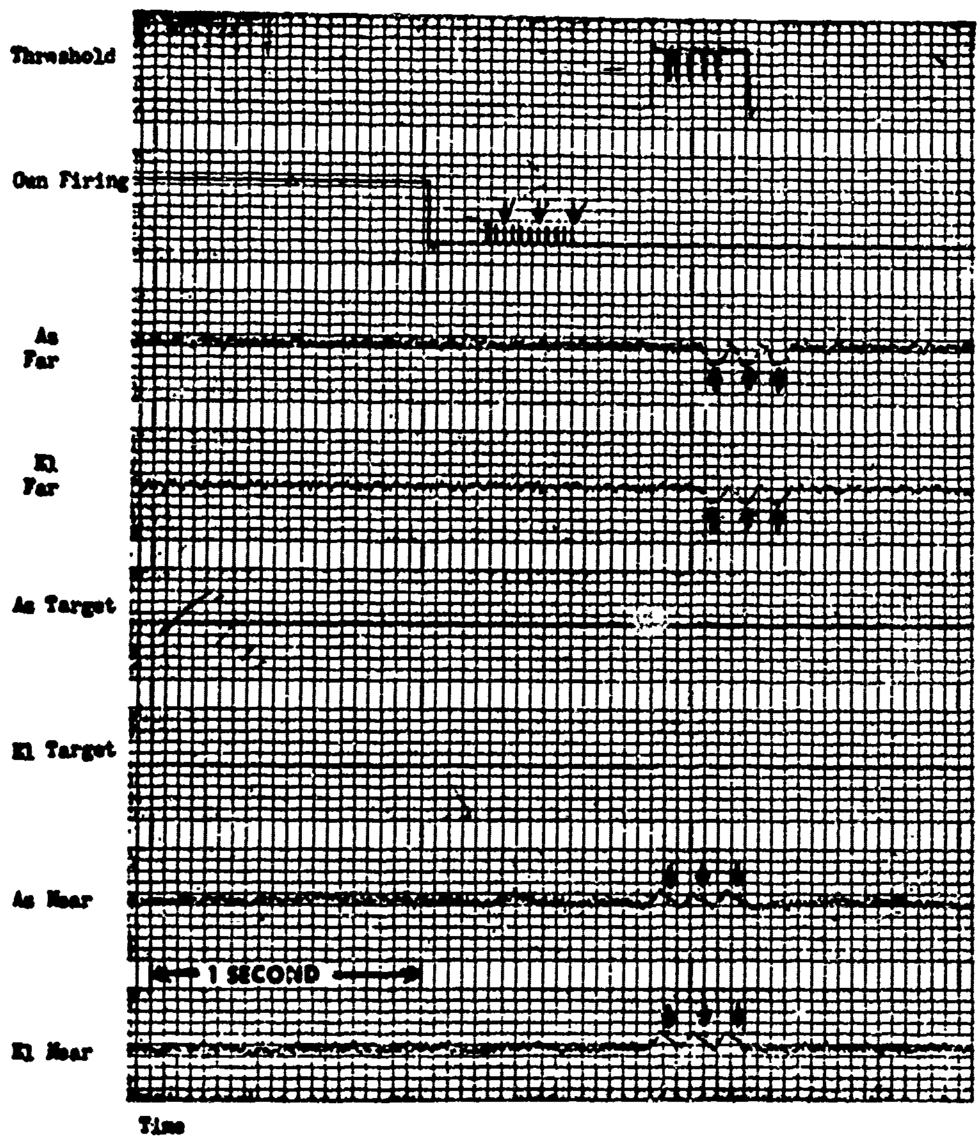

Threshold
Own Firing
Az
Far
El
Far
Az Target
El Target
Az Near
1 SECOND
El Near
Time

FIGURE 9.

 End