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A SURVEY OF THE DEVELOPMENT OF MORTAR LOCATION

By R. R. Crane

FR-2939

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Electronic Special Research Division
Radio Frequency Research Section

22 November 1946

A SURVEY OF THE DEVELOPMENT OF MORTAR LOCATION

By: R. R. Crane

- Report R-2939 -

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* * *

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ABSTRACT

This report is intended to crystallize the mortar location problem as of the present, correlating the strategic need with the technical possibilities of fulfilling this need. In order to do this thoroughly, most of the report has been concerned with the development of the various methods of mortar location. It is pointed out that the radar method remains the best approach to the mortar location problem. Past attempts at the solution of the problem and the numerous field tests with existing equipments are discussed. An analysis is made of the significance of all previous and contemporary work. The precise frequency is not determined, but the general frequency band between S-band and L-band is recommended. A mortar locating system is proposed.

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SECTION I

INTRODUCTION

1. Reference (1) established a project at the Naval Research Laboratory to study the general problem of the location of the firing point of mortars with the ultimate objective of developing a mortar locating radar equipment suitable for use by the U. S. Marine Corps.

2. In the fall of 1945 a conference was held at the Naval Research Laboratory between representatives of the Marine Corps Radar Design Section, Electronics Division of the Bureau of Ships and personnel of the Naval Research Laboratory. The purpose of the conference was to formulate a procedure to be followed in obtaining the desired objective. It was decided to divide the project into two distinct phases, the first phase to cover fundamental research and the second phase to cover equipment development.

3. It was anticipated that as a result of the first phase of the project a set of specifications would be produced outlining the military characteristics and specific mechanical and electrical design features desirable for a solution of the problem. The second phase would result in the construction of a breadboard model of an equipment complying with the requirements of the specifications resulting from phase one. Characteristics listed under reference (1) specifically for investigation during the first phase were: accuracy requirements, type of scan, type of presentation, type of radar, i.e. pulse, FM, CW, Doppler, or a combination of types and choice of frequency. Service requirements to be satisfied were also listed by the Marine Corps. They were: high mobility, light weight (approximately 1500 pounds maximum), ability to be quickly broken down into small packages for air and pack transport, and ease of field maintenance.

4. In general, this report is intended, firstly, to cover all previous work on mortar location up to and including 1945 in so far as this work might affect in any way the objectives of this report. A second objective is to describe those individual research projects set up by this project and discuss contemporary research projects elsewhere which bear upon the objectives of this report. A third objective is to analyze the facts presented by both the study of previous work on mortar location and by the study of contemporary, related research projects and to point out the progress made toward the determination of these general specifications which are the objectives of this report. Finally, a course of future action is recommended.

5. In presenting the report it is considered worthwhile to discuss at length the exact nature of the problem itself before pointing out possible solutions of the problem. For this reason the author

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has consulted with military experts and civilian scientists in an attempt to develop some concept of the type of weapons anticipated for future use. (See Section III). The type of radar which might best fit in with the anticipated military organization, tactics and available transportation, etc. has been discussed with these authorities. Although it is impossible to know precisely what the military requirements of this equipment ought to be, certain conclusions may be drawn from available information.

6. Section II chronologically covers significant previous and contemporary work on mortar location. A rigorous discussion of the problem and possible solutions are presented at length in Section III. Section IV consists of conclusions and recommendations. The bibliography of this report and the information available in Appendix 1 present a reasonably complete picture of the scientific efforts related to mortar location.

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SECTION II

THE HISTORY OF THE DEVELOPMENT OF MORTAR LOCATION

ORIGIN

7. During World War II one of the most potent weapons used was the mortar. Casualties from mortar fire in the Italian Alps were reported to have exceeded seventy percent of the total. In the Pacific Theater of Operations, during the Island Campaigns, more than fifty percent of Marine Corps casualties were sustained from mortar fire. On the beaches at Normandy it was estimated that each enemy mortar in operation caused 35 casualties to Allied troops during the landing phase, as compared to 11 casualties per operating machine gun. Only about eight percent of enemy mortars were knocked out by preparatory naval fire and approximately twenty percent by other weapons. It became quite apparent that during World War II effective counter-mortar devices were urgently needed. Section II of this report presents the chronological picture of the development of the mortar location art up to and including 1945.

8. Mortars range in caliber from 50 mm. to more than 300 mm. The smaller caliber equipment (e.g. the U.S. 60 and 81 mm mortars) may be transported and operated efficiently by three men, the operating period depending upon the ammunition supply. A mortar squad in the Marine Corps consists of six men, three of whom are used for ammunition and supply duties and three for transporting and operating the mortar. Mortar shells weight from 1.6 pounds to over 700 pounds. (See reference 50). The mortar can be set up and operated in a matter of seconds; skilled crews have no difficulty in firing ten or more rounds a minute, with at least fifty percent of the shells fired falling within a circle of 108 yards diameter centered about the target. The mortar is a high trajectory weapon. The effective range of the 81 mm. mortar varies from 200 to over 3000 yards, and the angle of departure varies from 45 to 85 degrees. The trajectory of the mortar is a reasonably close approximation to a parabola (reference 37), especially during the first two-thirds of the trajectory. The initial velocity increases from approximately 400 to 600 feet per second as the firing charge is increased. In this section of the report the primary concern was with smaller enemy mortars, similar to the U.S. 60 mm. and 81 mm. mortars and the Japanese 90 and 120 mm. mortars, since it was the smaller caliber mortar which possessed those physical and ballistic qualities which made the mortar so effective during World War II. In general, when the caliber of the mortar is not specified in this section it should be assumed to be of smaller caliber.

9. As paragraph 7 indicates, the urgency of counteracting the mortar became intense in the summer of 1944 and reached a peak during the early part of 1945. However, the location of enemy weapons is an

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obvious objective in warfare, and methods have long been sought to attain this objective. The first methods used were visual, but the disadvantages of those methods far outweighed the advantages. Limited range and accuracy and exposure to enemy fire were among the disadvantages. Sound equipment was used in World War I as a weapons locator and continued in use in World War II. However, the sound locator was generally used only against short range small caliber weapons, e.g. machine guns, etc. It was not until 13 September 1943, that a formal report on the location of mortars by sound was recorded. (See reference 2). An early memorandum on this subject was "Mortar Fire Location (Mortimer)", and included five reports on mortar location (reference 4). Three of these reports dealt with sound methods and two with radar methods. These enclosures were the earliest records discovered by the author dealing formally with mortar location.

10. On 13 September 1943, a report was circulated from Malvery, England, A.D.R.D.E., entitled, "The Location of Field Mortars by Sound" (one of the reports mentioned above) dealing with tests commenced on 20 August 1943. (See reference 2). The purpose of these experiments was "to ascertain variations in the time of arrival of a sound wave from the propellant charge of a Field mortar due to accidents of propagation caused by the low eddy structure of the atmosphere and ground disturbances. This is required in order to ascertain the minimum base length that can possibly be used in the measurement of the direction of the normal to the wave front to provide an accuracy of one degree for line in location." The actual field tests were carried out at Netheravon, England on four particular days. The type of sound equipment (British Mortimer type) used was not particularly important in this report. Subsequent improvements included in the final models being used at the end of the war will be mentioned later. Operations at Netheravon were with 4.2 and 3 inch mortars using full charges. Ranges were short (no exact figure was given), but results were favorable for an initial test. A description of the four-pen recorder used with the sound locating equipment was also included in this report; however, types of recorders will be considered later. The results of these experiments were obviously preliminary; some practical suggestions were included in the report, but few conclusions could be drawn.

11. The first record of mortar location by radar discovered was a brief report entitled, "Radar Location of Mortar Trials at Larkhill, November 1943" (reference 3). More specifically the purpose of the tests at Larkhill were "to determine the signal strength from a British 3-inch mortar bomb using AA No. 3 Mk. II" (a large British S-band, anti-aircraft radar). This first report discusses radar "siting", which was the subject of much discussion in many subsequent reports on ground activities with radar. In fact, the experimental test yielded unsatisfactory results due to the siting of the radar. The British immediately appreciated this, as shown by the following: "The radar was sited in a shallow valley with the skyline in the direction of

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mortar and target at 0 degrees elevation about 400 yards away. This reduced the clutter around the mortar to 2/1 at 0 degrees elevation. At an earlier site on top of a small rise with a clear view in the mortar direction the clutter was 20/1 at 0 degrees elevation, and small signals would have been undetectable below 8 degrees elevation." With this siting procedure, elevation angles of 1 degree and lower were used satisfactorily in detecting the mortar shell in flight. The procedure used for actually locating the firing point was what is now generally called the "multi-point system", which consists of plotting several points along the rising portion of the shell trajectory, extrapolating back a curve to the firing source. A detailed theoretical discussion of these methods for locating the firing points of shells is given in reference 37 and briefly in Section III of this report. Actually, the methods by which the points were obtained along the trajectory were quite crude as compared to the more recent methods, but the information sought was the same, and the method of obtaining the information was limited primarily by the accuracy of the equipment. Actually, the interest in this test was primarily to determine whether mortar shells could be detected at all by radar. Mortars were fired at different angles of fire with respect to the radar and a constant angle of departure of 70 degrees. Signal to noise ratios between 4/1 and 5/1 were observed at 5000 to 8000 yards range when the shell was dropping. Certain inconsistencies appeared during the test as signal strength was recorded and the angle of fire varied. Varying the angle of fire changes the aspect of the shell with respect to the radar beam. At that time the British wrote: "This discrepancy (in signal strength vs. shell aspect) can only be cleared up by direct measurement of bomb polar diagrams, which is being undertaken." In late 1944 a Canadian National Research Council report (reference 19) repeated this statement of the British suggesting bomb polar diagrams be made in the microwave region. In early 1945, reflection patterns of mortar shells for K, X, and S-band electromagnetic wave propagation were obtained at Ohio State University Research Foundation. Copies were given to the Canadian Research Council. (See Plate 1). These first trials of radar detection of mortar shells were sufficiently successful that some action was commenced to perfect the techniques of mortar location and seek additional information to form the basis for new design.

12. Developments continued in the location of mortars by sound, and several reports were put out in Europe on this subject in early 1944. Two of these were enclosed in the aforementioned memorandum (reference 2). (See paragraph 9). Later in this report the developments in sound location achieved at Camp Evans Signal Laboratory will be described in some detail. Certain limitations were readily apparent at this time in the use of sound as a mortar locator. In general, the range of detection of mortar fire, which was a function of meteorological conditions and could not very well be controlled, was limited to 2000 yards or less. The range and bearing accuracies were poor: 1 degree to 5 degrees in bearing, and plus or minus 100 to 500 yards in range. The performance of the equipment was affected by the inter-

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vening terrain and was rendered practically useless under random fire. It had the advantages of being reasonably light in weight and simple, and easy to install and operate. The reports mentioned (reference 2) deal with Mortimer I, II, and III, and time measuring devices coda, codar, codat and codak. Precise information is available on these sound equipments and recorders in JEIA files, although only the reports considering the application of these equipments to mortar location have been listed and considered in this report.

13. On 25 January 1944, a report was circulated on the radar location of mortars describing trials at Netheravon, England, held on 17 and 18 January 1944. It will be recalled that mortar location tests by sound had been proceeding for some time at Netheravon, so some experience in the process of locating mortars by instruments might be expected. As in the Larkhill tests, 3 inch and 4.2 inch mortars were used and were observed on the P.P.I.'s of the radar equipments SCR-517 and SCR-584. According to the report "Every effort was made to choose sites for these radars giving the minimum ground clutter along the path of the mortar bombs". The SCR-584 site was inferior, however, to the SCR-517 site. (See Table 1 for radar ranges against mortars.) The range was fixed between 2000 and 3000 yards for SCR-517 trials, and results were positive. Signals on the P.P.I. and the A-scope were seen, the signal to noise ratio on the A-scope being around 1/1 to 2/1. With the 86 rpm scan rate, occasional shells were detected on the P.P.I. The range for the SCR-584 was held at 8050 yards for the rise and 5900 yards for the drop in the trajectory. Results were also positive with the SCR-584. The signal to noise ratio was estimate to be 8/1 or better for both ascending and descending shells when the radar was searchlighted on the trajectory. When the antenna was manually scanned once a second through a 15 degrees sector, the echo from the mortar shell could easily be seen on the P.P.I. The British seemed disappointed that although the echoes of the shells were seen, the "narrow beams in the vertical plane rendered visible only small portions of the trajectory."

14. Summarizing briefly the origin of mortar location by radar: the desire to locate firing points was not new, sound methods having been used since World War I. In the summer of 1943, sound locating methods were used against mortars, which were becoming quite a menace as an anti-personnel weapon. The results were positive but not completely satisfactory. Subsequently, at Larkhill, England, in November 1943, a radar was used to locate mortars. These results were successful and were followed swiftly in January 1944 by even more successful tests with the SCR-584 and SCR-517 at Netheravon, England. These field trials were primarily under the authority of the British with some U. S. aid. Ranges of 8000 yards with signal to noise of 8/1 were observed on the SCR-584 against 3 inch and 4.2 inch mortar shells. The importance of siting and the peculiar effect of shell aspect on signal strength were noted. The multi-point method was used, though cumbersomely, to locate the firing point of a mortar.

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ACTIVITIES - JULY THROUGH SEPTEMBER - 1944

15. The discussion of the origin of mortar location covered the period through 8 April 1944. In this period two reports of field trials by radar had been reported. Gradually the advantages of the radar method of mortar location became apparent until interest in the sound method almost ceased, and a great deal of pressure was brought to bear on the use of radar methods. The possibilities of other methods, e.g. detection from heat radiated around the mortar shell body, etc. were not forgotten. However, radar showed much promise at the time and appeared to offer the most expeditious solution. Subsequently, Radiation Laboratory of MIT, Camp Evans Signal Laboratory (CESL), Belmar, N. J. and British activities, to mention a few, considered other methods and wrote papers on their results, but radar remained the best immediate solution. The British already knew that certain radars could detect mortar shells in flight at ranges sufficient for tactical purposes. The next move was to ascertain those characteristics which should be incorporated in a radar to best fit it for the role of a mortar locator.

16. The period of July 1944 through September 1944 produced several reports in Europe directly pertaining to mortar location. An OSRD Report (see reference 11) in the form of a London Mission inter-office memorandum described three radar sets recommended for use with field artillery to locate projectiles. The three equipments named were the "Artillery Shell Burst Set", the "Pulsed Doppler Watchdog Set", and the "Mortar Location Set". The Artillery Shell Burst Set was an adaptation of the X-band shell splash set developed by ADRDE. Reference 11 states: "This shell splash set is used in the Field Artillery role almost identically as it is used in shell splash work to correct both range and azimuth errors by presenting a bursting shell on the cathode ray tube" when the radar is directed toward the target. "In the case of the Field Artillery application, permanent echoes play an important and confusing part. It is of interest to note that slowly moving vehicles are distinguishable from echoes rather readily". When the target was completely obscured by clutter, an "offset ranging" method of getting on target was used. In that method ranging was done on some suitable reference point which was clear of permanent echoes, and which was only a few degrees from the preliminary target. When the range and azimuth on this reference point were corrected, the guns were turned to the primary target. Apparently this method was standard artillery procedure.

17. The second set, the Pulsed Doppler Watchdog Set, was made up of standard British airborne S-band components with a few modifications. Its primary use was the detection of moving targets. In principle it was similar to the AN/TPS-7, a Sperry Gyroscope Company equipment, which supersedes the Watchdog in all respects. The remarks concerning the Mortar Locating set in this reference were even more interesting. "For some time ADRDE has been working on the problem of locating enemy

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mortars by radar tracking of the shells therefrom. Their preliminary experiments have been so successful that they are asking Met-Vicks to produce six sets in a crash programme even before the trials on their experimental set, now almost completed at ADRDE, are finished". The antenna of this set was a 5 foot 6 inch paraboloidal dish which spun in azimuth at 60 rpm. It was an S-band equipment with peak power of approximately 500 kw. A second statement on this set was: "This rapid scanning is necessary since the mortar shells travel with such high velocity that their echoes would appear separated by too great a distance if a slow scanning rate were used". Later it was hoped to develop an r.f. switch so that two dishes could be mounted back-to-back and thus the effective scanning rate doubled. This was later done by both the British and the U. S. The electronic switch was developed at Radiation Laboratory, MIT, and preliminary experiments indicated that mortar shells could be detected out to 9000 yards. Another statement was: "They hope later to use the V-beam principle to obtain the heights of the shell". (See Section III). This, too, was later done by the British and the U.S. A second report (see reference 13) enclosed photographs of the British mortar locating equipment just described and repeated the description already given. The whole equipment was mounted in an International half-track vehicle.

18. From this equipment eventually evolved the British mortar locating set known as "Norman" (see Table 2). The description and history of the ultimate Norman is presented now. Norman finally became a V-beam, two-dish radar, similar in other respects to the earlier prototype. Two dishes were mounted back-to-back and rotated at 60 rpm with the transmitted power switched from one dish to the other as each dish swept through a given sector. This V-beam should not be confused with the V-beam of the U. S. mortar locating radar set AN/TPQ-2 or the Canadian mortar locating radar. (See Plates 3 and 2). The V-beam of Norman is similar to the American AN/CPS-6 system. The beams are such that a vertical plane normal to the direction of propagation of the system and some distance from the dish would have a V cut in its surface by the half power contours of the two beams with the base of the V close to the ground. Unfortunately, Norman never had much practical success, and as extensive tests were made with the SCR-584 and its adaptability to mortar location became more apparent, interest in the Norman project faded. In a conference with Major Hoskins of the British Radar Research and Development Establishment in Washington, D.C. on 23 October 1945, it was learned that activity on the Norman project had ceased before VE Day, and only two equipments were known to exist. These two equipments were stored in England for experimental use if desired. Apparently, in early 1945, the British decided to concentrate on the modifications of existing equipments and to leave the development of new equipments for mortar location to Canada and U.S., where some success with other design ideas had been met. The British had been doing basic work on propagation during this period which was of definite value in the choice of frequency for mortar location, but since this propagation research

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not directly instigated for mortar location it will not be discussed here. (See references 58 and 59.)

19. On 31 August 1944, a report (reference 10) discussed the results of initial British field trials made at the front near the River Orne in June, 1944. Very poor results were obtained. The radar, the GLIIIB, was situated 2000 to 4000 yards from the enemy lines, but only a few mortar shells were identified. The equipment was withdrawn from the front for further experiment, and 600 rounds (81 mm) were fired during the experiments, all but three being detected. The maximum workable range was found to be about 8000 yards. The report stated: "Accuracy depends to certain extent on the nature and the strength of the signal, but appears to be within 25 yards for range and 15 mils for bearing. (It should be noted that further inaccuracies may be caused by the process of conversion from the position of the bomb in the air to the position of the mortar on the ground, due to lack of knowledge of the angle of projection. This should not, however, be in excess of a further 100 yards error in range or bearing subject to further trials.)"

ACTIVITIES IN THE MEDITERRANEAN THEATER OF OPERATIONS

20. In the latter part of 1944 interest continued to increase in the location of mortars by radar, especially in the United States and Canada, which until this time had contributed little to the solution of the problem. During the fall of 1944 the Army Signal Corps commenced action in the United States on the problem of mortar location, and Canadian representatives held conferences with Radiation Laboratory, MIT, on this subject. The Canadians ran field tests on an experimental K-band radar against mortar fire at Petawawa, Canada. The United States Army Signal Laboratories originated a program of field tests for all existing radars which might possibly serve as mortar locators, and, in addition, began building the V-beam, K-band prototype of the present AN/TPQ-2, utilizing the consultative services of BTL. While this activity was carried on in the United States and Canada, extensive combined allied field tests were commenced in the Mediterranean Theater of Operations.

21. A complete discussion of the activities on mortar of a Combined British and American Field Radar Operations Section is included in a memorandum on file at the Office of the Chief Signal Officer. (See reference 17). The unit was formed in November, 1944, under the direction of the Major General Royal Artillery, 15 Army Group, "to use radar to locate ground targets on the 5th and 8th Army fronts." The operations were divided into several phases: Combat operations with existing equipment, modification of equipment for better operation, experimental work, training and the supervision of use and maintenance of equipment within formations in order to obtain the best results. But it was stressed that the spirit of the section was to be offensive,

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and the immediate purpose was to be the operational location of enemy targets in the priority (a) enemy mortars, (b) enemy artillery, and (c) enemy moving targets. This report discusses the activity up to the end of the Italian campaign. Survey reports were prepared by both the British and American Forces. Some of the more interesting information from these reports follows in paragraph 22.

22. The British used primarily the radar sets AA Number 3 Mk II(GL), AA Number 4 Mk III(LW), and the AA Number 3 Mk V (SCR-584). The AA Number 3 Mk II(GL), an S-band, gun-laying radar, resembles somewhat the SCR-584 in tactical use and electrical characteristics. The AA Number 4 Mk III(LW) is a light weight system on a frequency lower than L-band. It uses antenna arrays rather than paraboloids. The AA Number 3 Mk V is the US SCR-584 (S-band). Also used in conjunction with these equipments were mechanical "plotters" and at the end of the campaign the now well known RC-308 "Time Plotter" was being used. This Time Plotter will be discussed later. Both the U. S. and British operations were mainly against the smaller caliber mortars described earlier. The equipments mentioned were ultimately modified to include sector scan, the N^2 gate to produce more accurate range tracking, additional crystal protection, and a remote selsyn data box for reading and recording data. All of these modifications were made on the SCR-584, and on some of the other radars. Formal British trials were held in January, 1945, although some preliminary work had been done prior to this time. All equipments detected the mortar shell in flight, and accuracies with the SCR-584 radar using the mechanical plotter for locating the firing point were stated to be on the order of ±0.5 degrees in bearing and ±50 yards in range. However, detection and accuracy were quite poor when the line of fire of the mortar was directly toward the radar. The equipments were tried against moving tanks but with negative results. The GL radar, in general, was the most accurate and detected the greatest number of mortars. However, like the SCR-584, it was not usable in an advance since it was not sufficiently mobile. The LW radar performed satisfactorily in an advance, and ranges were reported up to 17,000 yards against small caliber mortar shells. In addition to this, the British designed four antenna arrays for the LW radar, which, when used with a newly developed electronic switch, permitted automatic angle tracking. Using either vertical or 45 degree polarization (the only polarizations tried), shells could be tracked approaching the radar from all angles. Previously, when using horizontal polarization, tracking was limited to those shells whose angle of fire, with respect to the radar beam, was more than 35 degrees, a rather important limitation. The LW radar also had some success in supporting vehicle movement and detected some ground targets such as tanks and vehicles. The British suggested in this resume of all their activities (reference 17) that a wave length between 50 cm and 100 cm employing the split beam principle might well prove to be the best compromise for a mortar locator set. "Although the trend of modern radar design is all in favor of microwave equipment, it is a fact that if a set on the lines of the LW radar with its great range and high mobility were designed with a higher degree of accuracy and requiring less maintenance to keep it working

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at maximum efficiency, it would be the better equipment. It is also worth noting that the microwave sets in general are unusable in heavy rain while an equipment with a longer wave length is relatively independent of weather conditions." It is quite apparent that British authorities in the MTO were not in complete agreement with the statements later made about the SCR-584, viz. that this was the best radar set for counter-mortar work in use at the end of the war.

23. The American branch of the Combined Operations Section operated primarily with the SCR-584, and at the end of the campaign in Italy, added the RC-308 to the SCR-584. The SCR-584 is an automatic tracking S-band radar (a later model was X-band) weighing 20,000 pounds. The modifications made on the SCR-584 were those described in paragraph 22. Results were very satisfactory with the SCR-584. Seventy-five enemy positions were located in one battle. The modifications proved successful, and the accuracies recorded were ± 50 yards (maximum) in range and ± 1 degree in bearing. Natural screening as an aid to operation was used and found advantageous. Screening angles were approximately 75 mils. In the final field trials in May 1945, results were reported very satisfactory. It was observed that 4.2-inch mortars were an easy target as compared with the 81 mm mortar. On the basis of this experience the American Branch recommended that future design be directed toward lighter and more mobile equipment, similar to the SCR-584 and combined with some automatic plotter such as the RC-308.

ACTIVITIES IN THE EUROPEAN THEATER OF OPERATIONS

24. The field activities in England and at the front will be discussed now from September 1944, the point when the previous discussion ended. Interest continued in England in the latter part of 1944, primarily in the AA Number 3 Mk II(GL 3(B), and during that time it was specially modified for mortar location; the modifications were quite similar to those already mentioned in paragraph 22. The early part of 1945 through March contained the greatest amount of activity, not only in Europe, but in the United States as well. The SCR-584 and similar radars were used with some success to extrapolate back along V-1 and V-2 bomb trajectories to locate the firing points. (See reference 60). For this purpose and for mortar location, the RC-308 was designed and built, some in France and some in Florence, Italy. Although the American radar set SCR-584 continued in the fore as the best radar for mortar location, reports pointed out its major failing was its size and weight. In the search for a lightweight system, a great deal of interest was evinced in the AN/APS-3 radar set. (See paragraph 25). It was given extensive field tests in England, modified slightly, and used at the front in Europe. The main trouble at the front seemed to be finding the enemy while they were using mortars. The AN/APS-4 and the AN/APG-16 were also considered for mortar location at this time, but results did not warrant continued interest, although the automatic tracking properties of the AN/APG-16 were worthy of additional study. The SCR-584 did not see much action at the front in the ETO as a mortar locator, although

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several interesting reports (see references 33 and 42) were made on its successful use as a road sentinel (i.e. detecting moving targets and troops.) One point is worth noting about activities with the SCR-584 at the front. In Holland, because of the flat land, no sites similar to those utilized elsewhere to screen out strong land return were available, and great difficulty was experienced obtaining positive results. Prior to the use of the RC-308, this factor which made the detection of mortar shells early in their trajectories impossible, rendered the radar useless. Methods of back extrapolation using the RC-308 would have been satisfactory, and it is apparent that in some cases the addition of a plotter is a necessity.

25. The SCR-584 has been discussed sufficiently to date and will again be referred to, but the AN/APS-3 is a new member of the mortar locating radar group. The AN/APS-3 is an X-band, airborne search radar weighing 250 pounds without primary power supply. Early in 1945 the AN/APS-3 was given a short field test by the Fifteenth Army to determine whether it was feasible to use the equipment in controlling counter-mortar fire. Operations were made against the 4.2-inch chemical mortar and the 81 mm mortar. Two modifications were made on this set; one limited the sector of scan to 60° and eliminated the vertical nod, and the other changed the polarization of the radiation from horizontal to vertical. The former modification was in line with tactical demands, and the latter was a result of the conviction that the mean mortar shell effective reflection area increased with this shift in polarization. This increase, in general, was later shown to be much less than originally believed. Usual siting procedures were used to reduce land clutter, The normal workable range with favorable aspect against the caliber shells mentioned above was about 4000 yards. A B-type presentation was used with a vertical marker line which could be placed by a hand control to bisect an echo, The bearing on the target was then read from the control knob. Range was determined by electrical range markers at 1000 yard intervals. Because of the method used to bring own fire to bear on enemy weapons, accurate absolute readings were not particularly important. The method used was to obtain the range and bearing of the mortar shell from the controls mentioned above and pass this information on to the counter-mortar fire team. The counter-mortar fire shell pips were then seen on the scope near the target, and the observer corrected the new shell echoes to coincide with the original enemy shell echo. This eliminated much effort or elaborate computing equipment and still gave fairly accurate results. It was noticed and stated in a report (see reference 35) that, "In common with all radars operating in this frequency band, this set is rendered inoperative during certain types of rain storms. This condition was encountered once during the present trials and persisted for approximately one hour". Several methods of fire adjustment were tried. Time intervals were measured to determine the quickest adjustment, and the fall of shots was plotted to determine the most accurate adjustment procedure. Times obtained were in the order of a few minutes, The firing in these tests was at angles of departure of about 900 mils, which is lower than generally used with mortars. The conclusions of these tests were that the AN/APS-3 was

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capable of being used for counter-mortar fire control within a range of approximately 4000 yards, that spotting was not precise, and that resulting counter fire, while it could be adjusted approximately to pass through the same point in space as the enemy fire, would not be precision fire. The time of adjustment could be considerably reduced by training and the use of several counter-mortars. The AN/APS-3 was light enough and small enough to be taken well forward and was suitable for use by chemical mortar battalions.

26. To describe briefly the RC-308: The plotter was designed to operate in conjunction with the automatic tracking features of the SCR-584. It was an automatic recorder which traced out on a roll of paper information concerning the trajectory of the missile as the SCR-584 followed it. Three plots were made: altitude vs. time (this plot was essentially a parabola), azimuth vs. time and range vs. time (these last two were essentially straight lines). By fitting a celluloid parabola to the parabolic curve of altitude vs. time and extrapolating back along the the trajectory to zero altitude (known or approximated), zero time was determined. Extrapolating back the straight line range and azimuth plots to this zero time with a correctly graduated rule gave the range and azimuth of the firing point directly. This unit was standardized by the Army as the RC-308, although early references to it were as the "time plotter". The equipment weighed about 125 pounds. An account of activity against the V-1 and V-2 bomb entitled "Army Radar for Big Ben Warning and AA Prediction, August 1944 through March 1945" (reference 60) describes the use of the SCR-584 and RC-308 for this purpose. Results against V-1 and V-2 bombs were quite successful considering the ranges involved.

27. To sum up the activities in the MTO and the ETO: Radar operations against mortars commenced formally in the latter part of 1943 and continued with increasing momentum through 1944 with activity in both the MTO and ETO. In early 1945 this activity became intense. The best modified British equipments were the radars A.A. Number 3 Mk II(GL III) and A.A. Number 4 Mk III (LW). The only new British contribution was the mortar locating radar Norman. The best U. S. equipments overseas were, first, the SCR-584, especially when used in conjunction with the RC-308, and second, the light weight AN/APS-3. The only new U. S. contribution was the aid in the design of the RC-308.

ACTIVITIES IN AMERICA - INTRODUCTORY

28. In the latter part of 1944 the U. S. Army intensified the activity on mortar location by radar and other means. Because of the favorable results obtained by the British, radar methods were emphasized as being more promising. Preliminary theoretical examinations into other possible methods were made at Camp Evans and at Radiation Laboratory, MIT. Developments with radar as a mortar locator proceeded in the U. S. and Europe in the same direction with field trials laying the basis for most advancement. In Europe, U. S. interest in the problem had been apparent early in 1944, leading into the combined U. S. and British

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activity in the MTO and the ETO. The first positive action recorded in OCSigO files on mortar location in the United States was a description of a conference held at Radiation Laboratory, MIT, on 9 November 1944. The gist of this conference was summed up as follows: "the present state of the radar art provides no completely adequate solution to the problem of locating mortars". The problem was ultimately assigned to Camp Evans with the Radiation Laboratory supplying consultative services. About this time a number of memoranda on mortar location (references 15, 16, and 19) were issued by the Radiation Laboratory proposing various methods of solving the problem and suggesting that basic research be undertaken. On 21 November 1944, a project to construct the K-band, V-beam prototype of a mortar locating equipment was discussed at Camp Evans Signal Laboratory. (See Table 2 and Plate 3.) This radar was to be engineered by the Bell Telephone Laboratories and produced under their direction. In addition to this action, to quote a report of 8 January 1945 concerning the activities at Camp Evans on mortar location, "a program for the investigation of possible uses of all available existing radar equipments as an interim means of mortar location was begun at Camp Evans Signal Laboratory around the first part of November 1944." It is quite evident that the U. S. was well-launched on an extensive effort in the winter of 1944-45 to produce both the interim and the longer range solution of the mortar location problem.

29. Work at Camp Evans on radar and sound and other methods of detecting shells will be discussed later. To complete the picture of the radars specifically designed for mortar location, it is necessary to mention the Canadian K-band mortar locator and the Radiation Laboratory "Whirling Dervish". (See Table 2). These were three of the four radar sets designed specifically for mortar location; "Norman" was the fourth. In addition, the several stop-gap measures used such as modifications of existing equipments and design of supplementary equipment for the radars, for example, the RC-308, contributed a great deal of essential design information. The most important of these modifications have already been mentioned.

ACTIVITIES IN CANADA

30. In a conference at Radiation Laboratory, MIT, it was stated that Canadian scientists had been in consultation during 1944 with Radiation Laboratory members on the design problems of a linear scanner, (a scanner whose plot of magnitude of angle scanned vs. time was practically a sawtooth, as opposed to the usual sine wave plot of nodding antennas). It was felt that this type of scanner might solve the V-beam mortar locating radar problems. (See also reference 57).

31. A report was promulgated in early 1945 by the Canadian Research Council on "Mortar Location Trials with an Experimental K-Band Radar Set Conducted at Petawana Military Camp, 4 December 1944 to 9 December 1944". (References 19 and 20). The purpose of these trials was to determine the efficiency of this type of K-band radar in locating enemy

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mortars, to investigate a technique of cooperation with such counter-mortar weapons as 3-inch mortars and 25-pounder guns, and to determine the maximum range at which 25-pounder air and ground bursts could be detected. The equipment used was a laboratory set-up built late in 1943 at MIT to test K-band R. F. components. The set used a Foster Conical scanner antenna, the transmitter output was approximately 7.5 kw peak, and the presentation was a B-scan on a 7-inch cathode-ray tube. The Foster Scanner scanned horizontally in a sawtooth fashion through 10° about thirty times per second. Pulse rates of 4000, 2000, and 500 per second and a pulse length of 0.5 microsecond were used. In the actual field trials, which were held on flat, treeless terrain, attempts were made to locate 3-inch mortar bombs and artillery shells in flight and by backward extrapolation to locate the firing source, also to locate ground and air bursts of shells. Accuracy of location in flight was found to be $\pm$ 50 yards in range and $\pm$ 0.5 degree in bearing. Extrapolation accuracy at 4000 yards range was $\pm$ 150 yards to $\pm$ 70 yards. Artillery shells could be located only when the base of the shell was presented to the radar beam. Twenty-five pounder air bursts were located to a maximum range of 3000 yards with an accuracy comparable to mortar bomb location, and ground bursts were detected to a maximum range of 3900 yards. Great difficulty was experienced with the problem of shell aspect. At the time of these tests, reflection patterns were not available on mortar bombs. This report, an earlier report, and a conference with cognizant Canadian authorities on mortar location (see references 18, 19, and 20) constitute the main sources of information on Canadian activities as reported here. It is anticipated, however, that additional information will be obtained in 1946 when the mortar locating equipment under development in Canada should be ready for field test.

32. It is believed that the major contribution of the Canadian investigations, excluding improvements in the set now under construction, were the methods devised to study the value of screen persistence of a radar scope and to study methods of searching for targets. The mechanism of this process is available in reference 20. A brief summary of this report follows: Two moving pictures were made. In one film, the flash echoes were placed quite randomly in time and position but varied in duration from 0.2 to 2.0 seconds. It was found that observations increased in accuracy with increasing durations of echo, up to a duration of 1.5 seconds. Thus, a persistent screen on which "flash" echoes remained for between one and two seconds was desirable. In the second film practical conditions were more closely simulated. Flash echoes were shown in series of six, with six-second intervals between the flashes at points on the screen representing the positions of shells fired from hypothetical mortars. The height of the projected picture was the same as that of the B-scope display, but the width was nine times as great (to represent 90° azimuth of the 10° of the B-scope). A blind was fitted in front of the picture, cut so that only 10° could be seen at one time, thus assuring that the opening in the blind had the same physical dimensions as the radar scope. Motion of the blind by the observer was then equivalent to searching with the radar set. Using this film, it was found that

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the most efficient method of searching for shells was to rotate the array in jumps of 10° or a little less, moving once every six seconds, the interval between rounds. With this technique and bursts of six rounds each, 84% of all bursts over a 50° sector were detected, although the angle of scan was only 10°. Section III contains more information on the choice of scan.

33. This report (reference 20) and the preliminary one (reference 19) seem to be the only ones of any significance written by Canadian scientists on this subject. Additional tests were made on the Admiralty shell splash locator type 931 K-band radar set at Halifax, Nova Scotia, against mortars with results similar to those mentioned. A complete report of these tests was not available. Out of the recommendations in their report (reference 20) on a K-band mortar locating radar, and utilizing the experiences of Camp Evans Signal Laboratory, the Canadian scientists engaged in the design and construction of a K-band, V-beam mortar locating radar set. Using the information obtained by Camp Evans with their V-beam mortar locating radar, the AN/TPQ-2, the Canadian scientists were able to improve their V-beam set considerably over the AN/TPQ-2, at least theoretically. Field trials should give more concrete information on the success of the Canadian mortar locating system.

ACTIVITIES AT CAMP EVANS SIGNAL LABORATORY

34. The Army Signal Corps Laboratory at Camp Evans contributed heavily to the solution of the mortar location problem here in the United States. The Bell Telephone Laboratories worked in conjunction with CESL, and the lengthy field tests at Fort Sill, Oklahoma, were under Camp Evans direction. A three-day seminar was arranged at Camp Evans for representatives of the Army, the Navy, and the Marine Corps. The seminar, which was called specifically to discuss radar, sound, and other methods for the detection of mortar shells, commenced 5 November 1945. (See reference 64).

35. A memorandum for file entitled "Conference on Enemy Mortar Location" (reference 25) discussed the characteristics of all Army radars used for mortar location, their potentialities as mortar locators, and suggested modifications which might be made to improve their performance. The report is detailed and discusses at length each equipment. Among those tested were the AN/TPS-1a, AN/TPS-2, AN/PPS-1, SCR-584, AN/TPS-3, AN/TPS-5, SCR-720, and the CA No. 1 Mk IV (Shell splash set). Progress continued at Camp Evans with various modifications of existing equipments, improved techniques, and the development of the AN/TPQ-2. Of the existing equipments, the SCR-584 with plotters, the AN/TPQ-3, and AN/TPQ-4, which was the official title of the previously mentioned modified AN/APS-3, were the important survivors.

36. A very complete account of the modified AN/TPS-3 (re-named the AN/TPQ-3) is available in a CESL report (reference 41). Briefly, the AN/TPS-3 is an L-band portable search radar. It was modified by adding cables so that for personnel safety the large antenna, which was difficult

to camouflage, could be separated about 100 feet from the radar console. An accurate ranging system and an off-center PPI were also added. The off-center PPI displaced the axis of rotation of the cathode ray beam to the bottom of the screen.

37. Additional work of some interest at Camp Evans was done on sound methods of locating mortars. In a CESL report of 12 October 1945 entitled "Mortar Location by Sound" (reference 56), the use of optical and seismic methods as well as sound arrival as a means of mortar location were discussed. The characteristics of the sound arrivals and modification of existing equipments were likewise considered. The general conclusions from these tests against 81 mm mortar shells were that the use of the flash and the flash-to-sound time to determine the range of the mortar was frequently not feasible because of the low intensity of the flash. The use of the seismic arrival was not feasible. No seismic arrival was detected from mortars at 1000 yards or greater range. Sound ranging on mortars proved feasible. Ranges up to 3000 yards were obtained against the 81 mm mortar and up to 5000 yards on the 90 mm mortar. The accuracy was fairly good for ranges under 2000 yards, half of the locations being within 30 yards in range and 10 yards in deflection of the mortar position.

38. The sound equipments developed at Camp Evans included the GR-6, the AN/TNS-2, and the AN/TND-2. In general, the sound detecting equipment was lightweight, about 100 pounds complete, and transportable by one or two men. It was simple to install and operate and was reasonably rugged. The dependable range of the equipments against 60 mm mortars under favorable conditions (as indicated in paragraph 39) was 2000 yards, and neither this range nor the accuracy was hampered too much by physical obstructions such as hills between the mortar and the microphones. The accuracy of the equipments varied roughly as the product of the complexity and the weight, and since this positioning of the mortar by sound was done by triangulation, the accuracy was also a function of the number of sets in a network, increasing as the number of sets increased. A reasonable accuracy for the equipments was 5° in bearing for any one bearing determination. Since the range is determined by triangulation, for a specific position the range accuracy may be calculated from the bearing accuracy. The unfavorable characteristics of the sound equipments for mortar location were the limited range and accuracy and the inability to operate satisfactorily under confused fire. It was clear that the sound equipments, while satisfying certain military demands, did not, inherently, conflict with the radar type of mortar locator.

ACTIVITIES AT FORT SILL

39. Since mortar location by radar was essentially a new operation, it was necessary to indoctrinate and train the teams of men who would operate the combat information center and to develop efficient, coordinated techniques. With representatives of Camp Evans, a program was originated at the Army Artillery School, Fort Sill, Oklahoma, to do this. Several

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tests were conducted, commencing early in 1945 and continuing until after VJ-Day.

40. A report entitled "Test 2, Report of Trials of Radar Sets SCR-584 and AN/TPS-3 for Mortar Location" was written describing the trials from 29 January to 16 February 1945 (reference 29). The object of the trials was to determine the accuracy of the above-mentioned sets and their feasibility for use. After the trials it was concluded that both the systems would be satisfactory as interim measures, and it was suggested that training manuals be written for the equipments as mortar locators. It appeared that a previous test, Test 1, had been made simply to determine the feasibility of the project, and this had proved satisfactory.

41. Test 3 was entitled "Tests of Radar Sets SCR-584 and AN/TPS-3 for Mortar Location Under Confused Condtions, 14 March 1945" (reference 30). The object of the tests was to determine the effects of confusion conditions such as multiple mortars, artillery shells and aircraft in the same vicinity, and mountainous terrain on the efficient detection of mortar shells in flight. The conclusions were that multiple mortars were confusing when firing simultaneously, but that if the mortars were spaced at 100 to 200 yards apart, individual firing points could be located. Continuous or "rapid fire" from single or multiple mortars did not interfere with effective mortar location. Secondly, artillery fire in general could be readily differentiated from mortar fire by both sets. Aircraft, falling objects, or birds could be distinguished from mortar shells only by careful study of the echo and its behavior. Thirdly, mortar shells could be located in mountainous terrain provided that the shells were fired so that the maximum ordinate was higher than the intervening terrain. A choice site was one which had an upward slope commencing about 300 yards away from the radar. A distant crest does not always provide sufficient screening, due to diffraction effects which may occur, and the higher the screening angle the larger the location error.

42. Test 4 was entitled "Test of Radar Sets SCR-584 and AN/TPS-3 for Adjustment of Fire, 21 March 1945" (reference 31). The object of the tests was to determine the degree of accuracy to which field artillery fire could be adjusted by the use of the two equipments mentioned. Operations were against the 4.2 inch mortar and the 105 mm howitzer. It was concluded that the SCR-584 was satisfactory for high angle artillery fire control when the shell aspect was favorable. A favorable aspect implies that when the angle of the horizontal line of fire was greater than 400 mils with respect to the radar, the AN/TPS-3 would detect the shell at all aspects reasonably well.

43. The final test, test 5, was entitled "Test of Radar Sets SCR-584 and AN/TPS-3 (Modified) for Locating Enemy Artillery, 22 March 1945" (reference 32). The object of the test was to determine the ability of these two equipments to locate enemy artillery and determine the accuracy attainable in this location. The conclusions were that the

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SCR-584 could not detect single artillery shells fired in a direction toward or very nearly toward the radar set. (See paragraph 40). The AN/TPS-3, as in test 4, however, operated satisfactorily in all aspects. The SCR-584 had a mean average error of 42.5 yards at a range of 4000 yards. The AN/TPS-3 had a mean average error of 32 yards in range and 15 mils in azimuth on high angle fire at a range of 8800 yards; on low angle fire the errors were 222 yards in range and 15 mils in azimuth. In the consideration of aspect both hoirzontal and vertical polarization were used.

OTHER ARMY REPORTS

44. During July and August, 1945, radar and sound equipments were field tested in a combined operation which simulated the battle conditions anticipated in Japan. This combined operation was known as project SPHINX. The Sphinx program was carried out at Camp Hood, Texas. In particular it was required that a way be found to reduce the Japanese type of cave fortifications. Because these equipments were not being operated by specially trained personnel or in a general location chosen primarily to guarantee good radar performance, it is interesting to note the range obtained and the comments made on the performance. The ranges obtained against the 81 mm mortar shells for the SCR-584 were 5900 to 6600 yards; for the AN/TPQ-3 they were 6500 yards to 7400 yards and for the AN/APS-3 they were 2000 to 3000 yards. Two sound equipments were also used, the GR-6, range of 1700 to 3000 yards, and the AN/PNS-1, range of 1700 to 3000 yards. On the general performance the SCR-584, AN/TPQ-3 and GR-6 were classified "good". The AN/APS-3 and the AN/PNS-1 were classified "fair". The AN/PNS-1 sound equipment was too inaccurate, having a range error of from 280 to 1300 yards, and the range of the AN/APS-3 was considered too limited.

45. To complete the picture on the U. S. Army activities the paper titled "Mortar Location by Radar" (reference 37) discussing mathematically the general problem of the detection of mortars, the methods of detecting mortars by radar and the accuracies involved, must be mentioned. The U.S. Army during 1945 promulgated several other papers on mortar location by radar. "Radar vs. Enemy Mortars" (reference 39) and the "Training Circular #27" (reference 42) on the use of the SCR-584 for mortar location are examples of those which are of interest.

ACTIVITY OF THE NAVY AND MARINE CORPS

46. Interest concentrated on the use of existing Army and Marine Corps radars. In addition, however, since the naval vessels in support of Marine landings possessed a large number of radars, in particular, some highly accurate fire-control radars and the methods for utilizing fire-control information rapidly and effectively, it was only natural that a consideration likewise be given to the use of this equipment as mortar and artillery detectors in support of landings. With the invasion of Japan imminent to add pressure to these activities, practically all

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existing Marine Corps radars and shipborne radar were tested against mortars (see references 50, 53, 54, 62, 63), and information already obtained by the United States, British and Canadian Armies were reviewed. However, while some preliminary tests occurred earlier, the main body of these Marine Corps and Naval tests were conducted during the summer of 1945, some after VJ-Day. With the advent of VJ-Day the Navy interest turned to other fields, and a thorough study of the mortar problem was not completed. With this in mind the Marine Corps set up this long-range project to determine the optimum characteristics of a radar set for mortar location.

47. In March, 1945, the Marine Corps interest in mortar location by radar was evidenced in a field test of existing Marine Corps radars at Camp Lejeune to determine the suitability of these equipments as mortar locators. (See reference 34). The equipments tested were the SO-7M, SO-12M, AN/TPS-1b, Mk 16 and Mk 20 Mod 1. These field tests and a subsequent field test in July of 1945 using the Mk 20 Mod 1, Mk 20 Mod 2, SO-7M and the SO-12M at Quantico, Va. constitute the major contributions of the Marine Corps in mortar location. A number of reports have been written on the naval problem of mortar location with shipborne radar. Appendix 1 of this report lists some of the field tests conducted by the Navy on mortar location. A Naval Research Laboratory Report (reference 53) covers the fire control problem with the shipborne radar, and an Operations Research Report (reference 50) considers the overall problem of shipborne radar for mortar location. Actually, the problem of mortar location by shipborne radar is different in many respects from the ground radar problem and most of the differences make the shipborne solution more difficult. For example, the echo from the land where the mortar is situated is not masked by surrounding terrain. In an actual test, the lobes of the Mk 12, a shipborne fire control A.A. radar, were such that land echoes over 5000 yards from the ship could still be seen with the antenna elevated more than 55 degrees above the horizon. Most shipborne radars were tested against mortar shells. The SP and Mk 12 gave dependable performance in the detection of mortar shells in flight but not when these shells were in the close vicinity of land echoes. The SP detected 81 mm mortar shells in flight at a range of 19,000 yards. The Mk 12 consistently tracked 81 mm mortar shells at ranges up to 14,000 yards. Certain conclusions might be drawn at this point from the work done with shipborne radars. First, the rapid azimuth scan type of presentation and extreme accuracy of the Mk 13 or the Mk 8 Mod 3 are worthwhile characteristics in a radar for mortar location. Second, the S-band radar, SP, and the L-band radar, Mk 12 gave better performance with regard to maximum range than the higher frequency X-band radar sets. Thirdly, the E-scan presentation of the Mk 22 Mod 1, providing it could be made sufficiently accurate without sacrificing some other requirement, provides a neat method of locating the firing point of a mortar shell without cumbersome plotting equipment.

48. In the initial field trials at Camp Lejeune the Marine Corps radar sets as mentioned were tested, and only the Mk 20 Mod 1 was recommended as a suitable interim set for mortar location. It was estimated

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that accuracies of the order of 250 yards in range and 15 mils in azimuth were obtained in locating the firing point of the mortar. Operation was satisfactory in adverse terrain conditions, and the shell echoes appeared on the A-scopes as "extremely strong signals", from 60 and 81 mm mortar shells. Subsequent tests at Quantico, Va. (reference 52) made with the SO-7M, SO-12M and the Mk 20 Mod 2 (laboratory model) proved the ability of all three equipments to detect mortar shells. The SO-12M is on X-band, the SO-7M on S-band, and the Mk 20 Mod 2 on L-band. An approximate maximum range of 12,000 yards on the 81 mm mortar shell was obtained with the SO-7M and the SO-12M and a range of 6000 yards with the Mk 20 Mod 2. The SO-12M was the most accurate of these three equipments with the SO-7M and the Mk 20 Mod 2, following in that order. Considering overall performance it was judged that the SO-7M and SO-12M were about equally suited for mortar location and were more suited than the Mk 20 Mod 2. If emphasis were placed on operation through rain and foliage, the Mk 20 Mod 2 was better than the SO-12M and the SO-7M. This report contains an analysis of the data obtained with reference to the design of a new mortar-locating radar, and some of the characteristics which, it was judged, should be included and would be desirable in a set for this purpose. These two reports do not agree. The discrepancy is probably due to differences in siting. The prime matter of importance however is not the successful operation of the SO-7M and SO-12M at Quantico but the apparent unfavorable maximum range obtained with the Mk 20 Mod 2. Furthermore, the excellent results with the Army L-band AN/TPQ-3 (17,000 yards range) and the Navy Mk 12 indicates that the frequency of the Mk 20 Mod 2 in the Quantico tests was not the source of the discrepancy. Since the use of L-band is contemplated, the point is emphasized. Future tests are planned with a more refined laboratory model of the Mk 20 Mod 2. Although work by BTL on this equipment was cancelled after VJ-Day, NRL is completing the aforementioned model with BTL plans.

SUMMARY

49. The resume of the Naval and Marine Corps activities on mortar location of 1945 completes Section II of this report. All of the subject matter except a consideration of targets and weapons that should be included for an analysis of this problem at present has been covered. A consideration of targets and weapons is the first topic of Section III. To summarize Section II: Historically, mortar location by radar originated in England in November 1943. In early 1944 field tests by combined Allied Forces were commenced in the Mediterranean Theater of Operations on the SCR-584, similar British equipment, and a lightweight low frequency British radar. Both types of equipment were modified and recommended for future use. Activities continued in the MTO until Italy surrendered. About the same time that this work was going on in the MTO, field tests were commenced in England on the SCR-584 heavy A.A. radar and the lightweight high frequency airborne radar sets, especially the AN/APS-3. Ultimately from the activity in both theaters there was developed sufficient demand, information and energy for the design and

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development of the RC-308 automatic time plotter to facilitate backward extrapolation with the automatic tracking SCR-584 for use against mortars and the V-1 and V-2 bombs. Some improvements were suggested in the AN/APS-3 for mortar location, and a radar specifically designed for mortar location, known as Norman, appeared. Lagging only slightly behind these activities in Europe the Army Signal Corps and the Canadian Army scientists took up this task, to be followed in 1945 by the Marine C orps and the Navy as they too felt the demand for a countermeasure against mortars. The Signal Corps conducted extensive field tests on existing equipment and also designed and built a prototype for a specific mortar locating radar which was to be the AN/TPQ-2. Of the radars listed only the SCR-584 with the RC-308, the AN/TPS-3 (modified to be the AN/TPQ-3), and the AN/APS-3 (modified to be the AN/TPQ-4) survived. The Canadian scientists with the help of Radiation Laboratory, MIT, commenced the design of a mortar locating radar similar to the AN/TPQ-2, and the Radiation Laboratory designed a mortar locator known as the "Whirling Dervish". The Marine Corps field tested its radars and found the Mk 20 Mod 1, SO-12M and SO-7M promising. The Navy performed the same operation on shipborne radars. The Mk 13 and Mk 8 Mod 3 offered most promise. All this information points out that a solution to the problem of mortar location is still in the offing. Section III of this report is meant to crystallize the problem and solve at least part of it.

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SECTION III

ANALYSIS

DESIGN FUNDAMENTALS

50. In general, for the remainder of this report the smaller caliber mortar and howitzer (up to 155 mm) will be considered. The polar reflection patterns of the shells that have been measured will be considered in the choice of frequency. The trajectory of the target and the accuracy of the weapons will be considered in the choice of method to be used in locating the mortar site.

51. An incidental but practical consideration in fixing the weight, size and mobility of the final equipment is the demand placed upon the equipment for mobility. The radar equipment should be as mobile as but no more mobile than the weapons with which it must operate. The method of orientation between the radar and the weapons may permit them to operate from widely separated positions; however, the mobility demand remains approximately the same.

52. The original four requirements placed on the system by the Marine Corps were that the equipment would be highly mobile, lightweight, easily broken down into compact units and capable of discriminating against other targets. Thus any solution of this problem is concerned with (a) the ability to handle traffic, (b) the ability to control a given area, (c) the ability to select and recognize the target, (d) the accuracy; and having fulfilled satisfactorily (a), (b), (c) and (d), (e) the ability to meet the general demands placed upon the equipment because of its particular tactical use.

TRAFFIC HANDLING PROBLEM

53. The traffic handling ability of the mortar locating radar had already received considerable attention. At any rate, the ability to handle traffic is clearly important. Obviously this ability is a function of the delay time in detecting when a mortar is firing shells and the time required to obtain the necessary information from the detected shell and present this information in the form and at the place required. Let us consider first the delay time. One approach to the delay time problem is to require that the first shell fired be detected during its trajectory. The AN/TPQ-2 mortar locating radar will detect the first shell fired within the sector which it is scanning as soon as the shell is no longer masked by terrain. In approximately one minute this information can be put in the form of a range and bearing location with respect to the radar, corrected for any difference in height between the mortar and the radar. Actually at present the above information is unconfirmed since insufficient field data is available on the AN/TPQ-2. The second approach is to permit some number of shells to be fired before requiring detection. The SCR-584 performed quite satisfactorily in this fashion; that is, when a shell was detected in the beam of the SCR-584, the first

shell, in general, served only to orient the system. The beam was then searchlighted and the gate used for automatic tracking set up at that point. The next shell fired was detected and automatically tracked. Operating in conjunction with the RC-308, at the end of the second shell trajectory, a continuous graph of the information obtained from the shell was available. By extrapolation (as previously described) the range and bearing with respect to the radar of the mortar shell was found. In general, this operation when the mortar fired in fairly rapid fashion took less than five minutes and often as little as two minutes. Of course, if the enemy never fired more than one shell per position the position would never be detected by this method, but the radar has at least harassed the enemy. To justify this method further, it is a fact that in general several shells must be fired from a mortar before it "sets" into its new position, and any attempt at aiming the mortar prior to this setting is highly inaccurate. In addition, against the cave warfare of the Japanese this method would have been effective. The method used by the AN/TPQ-3 and the Mk 20 Mod 2 and SO-series were even more dependent on successive shells being fired for they did not possess automatic tracking and were forced to detect both the rise and fall of the shell trajectory for accurate azimuth and trajectory approximations. It can be seen that theoretically the AN/TPQ-2 method described is the better method from the standpoint of delay time and information time. In addition to the AN/TPQ-2 the Canadian mortar location set, the British Norman and the U. S. Whirling Dervish attempted the same approach. For this reason it will be discussed at length here.

54. The AN/TPQ-2 and the Canadian mortar locating radar now in development used the same general method of obtaining the rapid scan. Both employed a linear scanner. (See reference 21). The AN/TPQ-2 employed the Lewis Scanner, and the Canadian equipment employed the Foster scanner. The radar beam is made to scan rapidly from one side of the coverage sector to the other side, then snap back with a minimum time delay to the first position and repeat this procedure. A plot of angle magnitude with respect to the first beam position vs. time would produce a sawtooth function. In designing the scanner for the AN/TPQ-2 the coverage sector was made as large as possible and still sweep the radar beam through the sector with sufficient frequency that a mortar shell would always be hit by five or more pulses from the radar. These considerations for the AN/TPQ-2 led to a coverage sector of 20° through which the beam was swept about 30 times per second. Obviously the maximum delay time could be no more than 1/30th of a second. For the Canadian radar the sector was tentatively set at 10° and the sweep frequency about 30 times per second. It will be recalled that in Section II paragraph 32 the Canadian approach to the coverage and delay time problem was discussed. The advantage of scanning 10° as opposed to 20° without much loss in effectiveness is primarily an engineering gain, reducing the mechanical design problem of the linear scanner considerably. This fact was reflected in the ratio of the weights of the Canadian scanning mechanism to the AN/TPQ-2 scanning mechanism, which was more than one to four.

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55. The Whirling Dervish design solved the problem in a slightly different fashion. Whereas the AN/TPQ-2 and Canadian mortar radar developed the sawtooth beam sweep with linear scanning, the Whirling Dervish produced the same effect by rotating four radar reflector dishes physically situated back-to-back. A switch transmitted power to each dish as it swept through a given 90° sector. Practically the sector would be slightly less than 90° due to the delay time of the switch. The dishes were rotated at 60 rpm. Perfect sector coverage as obtained with the former two equipments could not be obtained with this slow rotation speed, but it would be theoretically possible with increased rotation speed. Practically it is doubtful if engineering considerations would permit much larger rotation speeds. It is obvious that a sufficiently large radar beam width would decrease the rotation speed to any desired amount and still insure perfect sector coverage. However, using a V-beam (AN/TPQ-2 type) arrangement, a narrow beam is essential to produce sufficient accuracy in the positioning of the mortar shell in space.

56. Using the method employed by these radars for rapid sector scan, the initial delay time in the pickup of the mortar shells after a mortar has commenced to fire in a given sector is practically negligible. The initial delay time in the two point detection method of the AN/TPQ-3, etc., and the automatic tracking radar set SCR-584 was discussed in paragraph 53. The information time must now be considered.

57. Essentially there are three methods of translating radar information as obtained in the usual fashion into useful information for combat information. It is not important to this discussion whether the information is desired in polar coordinates with respect to the radar or in the rectangular coordinates of a map. These methods arise out of the three possible situations: (a) the case where the information obtained by the radar locates a limited number of discrete points on the shell trajectory as blips on a radar screen, (b) the case where the radar continuously locates the mortar shell in flight but does not store this information in the radar, (c) the case where the radar locates in a near continuous fashion the mortar shell in flight and stores this information on the radar screen.

58. For the case of two discrete points as exemplified by the radars using the V-beam principle, mechanical measurement operated by an observer is necessary. The procedure is to extract by some measuring device the information existing on the radar screen and at the same time automatically compute the approximate position on the earth's surface of the mortar site in whatever terms desired. It is clear that the information time of method (a) is quite small and the operation simple. The primary objection to the system lies in the inaccuracy. Method (b) consists of automatically tracking the shell in its trajectory and plotting this information at the same time. The time of flight of a mortar shell does not, in general, exceed 30 seconds. When approximately one-third or more of the shell trajectory has been recorded, at the discretion of the operator, extrapolation may be performed to obtain

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the information as desired. This method is clearly more complex and longer than the first method, but it does increase accuracy and decrease the dependance on operator reflex. The third method, which was attempted in the British Norman, utilized a different type of V-beam from the other systems as described in Section II paragraph 18. The result of using this type of V-beam was a set of points somewhat in the form of a parabola existing on the radar screen and another set of points forming approximately a straight line. One set of points was derived from each beam. A simple backward extrapolation on the screen itself of these two point sets produced a single point of interesection which was the position of the mortar site. The Norman resembled in scan the Whirling Dervish, that is, it had two radar antennas back-to-back rotating at 60 rpm. and it used an electronic switch to control the sector scanned. The initial delay time was thus similar to that of the Whirling Dervish. The method of translating the radar information into useful information was quite simplified from all standpoints. The major disadvantage of this method is the inaccuracy. Field trials with Norman in England were apparently unsatisfactory. Recently the AN/CPS-6, which also utilizes this particular V-beam method for height-finding has been field tested; however no attempt was made to obtain the accuracies required by the mortar problem, and as a result the field report presently available (reference 67) gives only a qualitative picture. Emphasis will not be placed on this system here since sufficient information is not available. The Norman project has, however, been repeatedly mentioned for the specific point now being considered, i.e. the simplicity and ease of the method of extrapolation.

59. The rapid scan search method logically aligns itself with the discrete point information method to form one system, and the slow scan search method aligns itself with the automatic tracking information to form another system. The previously discussed Norman system is an exception, since it combines a rapid scan with a multipoint method. From the standpoint of traffic handling ability alone the former system is better than the second. However, from a general consideration of the problem it can be seen that the difference is one of order rather than degree. So that it should not be particularly important if one system could at maximum locate 30 mortar positions in one hour while a different system could locate only 15 positions in one hour. What is important is rather that the system be able to locate a minimum number which would be a reasonable approximation of the maximum number of mortars generally met in an area which the system governs. According to the military authorities, 15 mortar locations an hour would be satisfactory. In fact the case where 30 mortar postions lay within the area governed by the system would be exceptional. Practical trials on the problem of traffic are not comprehensive, but it is indicated that within the sector scanned the AN/TPQ-2 could probably determine over 30 mortar sites an hour while the SCR-584 could probably determine over 15 mortar sites an hour. Consideration (b) and (c) of paragraph 52 immediately arise at this point.

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CONTROL OF A GIVEN AREA

60. In the previous discussion no consideration was given to the probability that a shell fired in a given area would be detected. From discussion with military personnel, a consideration of the geometry of mortar location and the requirement that this sytem be lightweight, a more or less arbitrary figure for a maximum range under all types of conditions was set at 10,000 yards against 81 mm M 43 mortar shells at all aspects anticipated in the field. This 10,000 yard range figure is near the maximum conceivable under the conditions stated, and it is not at all certain that a probability of one can be guaranteed even with the radar beam searchlighted on the coverage area. Previously the military characteristics required a sector coverage of 90° or more. However, it should be pointed out that the probability of detecting all shells fired in a 90° sector with one radar is less than unity.

61. The factors to be considered are the usual parameters in the radar system, those affecting the propagation of microwaves, and the type of target. Suitable references are available on the usual parameters. The mortar problem, however, lays special stress on the scan loss, the effect on a wide frequency spread of microwave transmission through adverse weather conditions and the relative reflection of these waves from different types of terrain and from the special target mentioned. Reference 63, a memorandum, describes an approach to the measurement of the effective reflection of rain and types of terrain for discrete microwave transmission bands. Calculations are being made on the reflection of rain in the microwave region and a series of experiments planned to check the results. The measurement of the reflection from rain is necessary so that the choice of frequency for the system may guarantee operation through adverse weather conditions. It is possible that some device, such as circular polarization of the radiated energy, may be employed so that the upper limit of frequency at which adverse weather conditions becomes significant may be raised. The use of circular polarization will reduce the sensitivity of the radar by a few db., but will serve to improve its performance through rain. If the 10,000 yard figure given for maximum range were retained and operation through rain made an absolute requisite of the radar system, present information indicates that the highest transmission frequency that should be used would be in the neighborhood of 2000 megacycles. The highest frequency is desirable to limit the weight and size of the system.

62. The measurement of reflection from different types of terrain is desirable because it determines the discrimination between shell echo and terrain echo and indicates the degree to which MTI is needed and also influences the choice of frequency. The measurement of refraction and diffraction by terrain is important in accuracy considerations and the tactical use of the radar. Some preliminary work has been done on the reflection from terrain, but it is at present inconclusive. Slightly more has been done by the British (reference 58)

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on the diffraction and refraction of microwave transmission by terrain, and some conclusions have been drawn. Some of the British work was performed specifically to aid the solution of the mortar problem. Information available in the United States is limited, and it is not known if the British pursued their work after the summer of 1945. Indications were that they intended to do so.

63. The effective reflection area, σ , of the target has been studied by the Ohio State Research Foundation. Measurements were made on the target mentioned in paragraph 60, the 81 mm M 43 mortar shell. The measurements were of the reflection from the shell at all aspects and on several frequencies, viz. K-band, X-band and S-band. The information obtained was not exhaustive but revealed several interesting facts. The reflection pattern from the shell in the K-band region indicated that the σ was at a minimum in the region within 60° of the nose aspect. Furthermore the change in σ was greater than 100 db from the side aspect to this angle around the nose aspect. In the reflection pattern for X-band the null angle decreased to about 30°, and the σ of the nose aspect increased. The reflection pattern of S-band continued in the same direction. These measurements were the only ones taken. It is probable that the nature of the pattern at L-band will be entirely different from that measured in the X and K-bands, since here the dimensions of the shell become comparable to a half wavelength. No measurement in this region has been made as yet. However, experience in a qualitative fashion corroborates this belief, since it has been reported that on L-band the effect of aspect is much less than at the higher frequencies. This fact coupled with the fact that reflection from rain at L-band is comparatively small suggests that choice of frequency in this region should be seriously considered.

64. The scan loss problem has received considerable attention from a number of scientists, especially toward the end of the last war when rapid scanning systems were being built. Some information on db. loss as a function of db. parameters is available.* A number of other factors affecting scan loss have only been touched upon. NRL and Johns Hopkins University, in particular, have commenced work on the over all problem of what is conveniently described as scan loss. NRL and a group at Johns Hopkins University are cooperating on a thorough study of this problem. Only tentative results have as yet been obtained.

65. Neglecting propagation considerations and assuming that the mortar shell can be detected if it remains in the radar beam a certain period and does not exceed a certain range from the radar, methods of searching for the mortar can be considered. Under these conditions, with the additional assumption of a reasonable trajectory and velocity of the mortar shell, the consideration is a probability function. To date two known attempts have been made to solve parts of this problem. One of these attempts was discussed at length in paragraph 32 (reference 35) and was carried out by the Canadian scientists in connection with their

* See references 69 and 70.

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rapid scan mortar radar. The second attempt was made at NRL. In the NRL report functions were derived for probability including beam shape, scan speed in degrees scanned per second, pulse repetition frequency (it was assumed that 5 pulses per beam width per target insured a probability of one for detection), range, and dead time between scans. The derived function for probability is: (See reference 68, page 24)

$$Q = \frac{R\alpha S}{\theta K v \omega \phi e}\sqrt{(\omega\theta e)^2 - (\alpha n S)^2}$$

$$S = \sqrt{\theta^2 + \left(\frac{K\omega v}{R\dot{\alpha}}\right)^2}$$

where

R = range, in yards
α scanning rate, in degrees per second
S = (as above)
θ = vertical beam width, degrees
ω horizontal beam width, degrees
ϕ = scanning sector, degrees
v = velocity of shell, ft. per second
e radar pulses rate, pulses per second
n = number of pulses required to strike the target for detection
K = 19.10 (a conversion factor)
Q = probability of detection of the mortar shell. Since is fixed at 5, Q may be greater than unity numerically.

SELECTION AND RECOGNITION OF THE TARGET

66. In the previous two considerations the main concern was with the mortar problem specifically. The conclusions drawn from the extensive field tests held at Fort Sill (see Section II, paragraph 39) should be recalled. In these tests different targets were used to determine whether they could be detected at all and the mortar target was tested under confused conditions to determine whether it could be recognized. Test 3 of the Fort Sill tests was performed specifically to determine the effects of confused conditions such as multiple mortar, artillery shells and aircraft in the same vicinity and mountainous terrain. The conclusions are worth repeating here. They were that multiple mortars were confusing when firing simultaneously; however, if the mortars were spaced at 100 to 200 yards apart, individual firing points could be located. Continuous or rapid fire from single or multiple mortars was not an effective measure to prevent mortar location. Secondly, artillery fire in general could be readily identified. Aircraft, falling objects, or birds could be distinguished from mortar shells only by careful study of the echo and its behavior. Thirdly, mortar shells could be located in mountainous terrain provided that mortar shells were fired so that the maximum ordinate was higher than the intervening terrain. Test 5 indicated that artillery shells could be detected by radars at a range of over 5000 yards, and test 6 demonstrated that ground targets could be detected by the SCR-584. Actually, with regard to mountainous terrain, the automatic tracking feature of the SCR-584 permits a greater

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liberty in the selection of the radar site than with the AN/TPQ-3. The AN/TPQ-2, because of the sharp cut-off of its narrow beams, is almost independent of siting difficulties.

67. For the detection of moving ground targets and to facilitate the detection of airborne targets close to the earth's surface a form of MTI would be valuable. For this reason other types of radars such as CW, FM and Doppler radars have been considered, and in addition a coherent pulse MTI as part of a pulse system. However, the CW, FM and Doppler radars presently in development are prohibitive from the standpoint of either accuracy or discrimination against other moving targets or both. There is no exception to this rule along these lines at present, and none seems in the offing. The alternative procedure is to have some MTI scheme which may be used in conjunction with the pulse type radar. Insufficient information on the performance of MTI does not permit definite statements concerning it. At the present time several scientific concerns are interested in developing MTI and an extensive field test is being conducted on MTI by BTL under a Bureau of Ships contract sponsored by the Marine Corps. Tentative conclusions from these tests tend to corroborate the pessimistic theoretical outlook regarding the use of MTI with any rapid scanning or automatic tracking radar. With regard to a more lightweight and rugged coherent oscillator MTI, further work is being done on solid delay lines and storage tubes of different types for use with MTI and other purposes. The storage tube still does not solve the problem of rapid scan and automatic tracking but is a step in the proper direction. Providing this type of MTI does not satisfy the system requirements, a more simple MTI such as the Aural Doppler could be used to aid in the search for ground targets. It is hoped that the coherent oscillator type MTI attachment or some similar method will be perfected within a few years so that most of the problems requiring MTI in this system might be solved. The combination of the pulse radar with MTI appears to be the most satisfactory type of system for the purpose stated in Section I paragraph 1.

THE ACCURACY

68. The accuracy of the mortar locating radar is of fundamental importance. Radars exist which can locate mortars more accurately than the counter weapons can strike a known fixed target in that area. Where weight and mobility are no object the design philosophy may well be to build the most accurate system. However, in the case of the mortar locating radar it is necessary to design for the optimum relationship between those factors affecting the tactical employment of the radar and the radar accuracy. For this reason it is necessary to consider in detail the errors of the probable system of locating the mortar of which the radar error is but one part.

69. As brought out in reference 37, for effective counter fire the error in the assumed position of the target should be substantially equal to or less than the probable error of the counter weapon. A

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further consideration of the problem demonstrated that the optimum arrangement occurred when these two errors were equal. Ballistic error is denoted by probability curves. A reasonable approximation of the 0.5 probability curves of the 105 mm. howitzer is a circle of radius 50 yards. This means that 50% of the shells fired from a 105 mm howitzer will land within 50 yards of a known target position. It is now necessary to design the radar and develop the technique of locating mortars and orienting the radar and counter weapon so that the combined errors will be less than $\pm$ 50 yards in range and azimuth. In the following discussion it is convenient to take the maximum range at 10,000 yards.

70. The radar error is composed of two errors, the method error and the equipment error. A thorough investigation of the method error has been carried out (reference 37). The results of this work exclude the orientation error and the equipment error but merely equated the method error and the ballistic error. The methods were compared on the basis of the relative heights at which the mortar shell must be detected in each case to locate the mortar site within a 50 yard radius circle. The method error exists because the mortar shell is not detected adjacent to the firing point, and some method of extrapolation is necessary. There is a variety of methods because there is a variety of ways of getting information on the shell trajectories and of extrapolating this information. It can be seen that the least amount of information which a radar could supply would be the location of the mortar shell at one point on its trajectory while the most information would be a continuous plot of the mortar shell position on its trajectory.

71 The previous three considerations, that is, traffic, control area, and selection, tend to limit the previously known number of methods which might practically solve the mortar problem to two. They are the continuous tracking method and the V-beam instantaneous locating system. These methods are exemplified by the latest mortar locating systems. From the standpoint of accuracy these two systems again stand out as the most satisfactory. The conclusions drawn in an earlier study (reference 37) were that the continuous tracking method is the best and should be used whenever the required equipment is available and field conditions permit. The two point method may be used under the majority of field conditions, especially when full use is made of all information. It has been demonstrated mathematically that with continuous tracking, as long as a reasonable percentage of the shell trajectory was obtained, it was not necessary to have an upper limit on the first point of detection of the shell above the earth. Using the two point fixed angle extrapolation in order to obtain the accuracy described in paragraph 69, it would be necessary to detect the mortar shell at the first point before it has risen more than 120 yards above the firing point on its trajectory. At times this limitation could render the system useless.

PHYSICAL REQUIREMENTS

72. The Marine Corps has placed four requirements on the mortar locating system in addition to the fundamental requirement of locating

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mortars; of these requirements three were physical requirements. They were light weight, high mobility, and ease of breakdown into compact units. What the Marine Corps desires, however, is the lightest, most mobile system which satisfactorily meets requirements (a), (b), (c), and (d) of paragraph 52. An example of a heavy system is the SCR-584; an example of a lightweight system is the sound equipment, Type GR6. The AN/TPQ-2 is the closest approach to the medium weight radar system. A sufficiently lightweight system should satisfactorily meet the requirements of high mobility and simple breakdown.

73. From the tactical use of this equipment certain other physical demands which should be met are apparent. The equipment would be placed within 4000 yards of the enemy lines, and a line of sight path to the target would be necessary. Since the target must be located as close above the firing point as possible for the desired accuracy, the installation of this equipment would be in the view of the enemy. Thus, that part of the equipment which must be so located should be made as insignificant as possible. Likewise because of this position in combat the simplicity of operation should be stressed. Any installation or alignment procedure must be held to a minimum. After arrival in position the system should be operating normally within a few minutes.

74. Of existing systems only the AN/TPQ-2 and the SCR-584 could possibly meet the requirements of (a), (b), (c), and (d). Actually neither does meet these requirements in full, and neither can meet requirement (e). However, it is apparent that with additional fundamental information, a proper combination of the properties of previous mortar locators and expert engineering, it is quite probable that a system could be designed which would satisfactorily meet all five requirements. It is equally probable that this system would weigh between 1000 and 1500 pounds, and the consideration of weight would apply a constant pressure to the design of the system at the possible expense of some feature. This, however, is one approach to the problem, and with this in mind a survey was made at NRL (reference 66) on the application of automatic tracking to the mortar problem. The results of the survey indicate that a lightweight automatic tracking unit could be constructed to satisfactorily meet the requirements of this system. Another survey into the applications of the sub-miniature tubes and components into radar circuits indicates that in the near future these lightweight articles may be used in radars of the type under consideration. These surveys bear out the conjecture that a medium weight system could be engineered. However, another approach to the problem, of course, exists, and that is to search for a new solution which might render the problem of meeting the requirements more simple. An example of this type is the triangulation method of locating the mortar site (reference 15).

SUMMARY

75. From the past discussion some conclusions concerning the system characteristics specifically listed (see paragraph 3) for consideration in this project may be drawn.

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TRANSMITTER FREQUENCY: From the standpoint of system potentialities and light weight, a frequency in the neighborhood of X-band or higher seems the logical choice. However, from the standpoint of the reflection from rain and from the shell reflection characteristics a frequency in the region between S and L-band would be the logical choice. Since at ranges of 10,000 yards or less it is the reflection from rain rather than the attenuation through the rain which is the more serious factor, then the volume of the pulse packet is of great importance. This volume is a function of range, beam shape and pulse width. The range is short, and the other two factors for this problem may be chosen to minimize the size of the pulse packet. Theoretical calculations indicate that with proper beam width and pulse length the effective reflection from rain might be made negligible at S-band and possibly higher frequencies. Practical experience does not corroborate the theoretical calculations, but actually no thorough attempt has been made to check the theoretical calculations for reflection from rain. Such measurements are essential to proper choice of frequency for this problem since the design philosophy on this point is to choose the highest possible frequency compatible with successful operation through rain. In addition to these measurements, a study of the σ of different sized shells as measured for frequencies below S-band should be carried out. A period of nine months or more would be necessary to perform these measurements.

ACCURACY REQUIREMENTS: For the two-point system an accuracy in angle of $\pm$ 1.5 mils and in range of $\pm$ 15 yards would be required. For the multi-point or automatic tracking system an accuracy in angle of $\pm$ 8 mils and in range of $\pm$ 25 yards would be required. Less accuracy is needed in the latter case since more information is obtained on the shell trajectory. The above figures are approximate but give the order of accuracy.

TYPE OF SCAN: Additional information on the exact military requirements is necessary before setting the optimum type of scan. Several possibilities are under consideration. One possible choice is described in paragraph 78.

TYPE OF PRESENTATION: The presentation can only be determined after the scan and general design of the system have been completed. However, the presentation should be such that one or two men may conveniently operate the system and obtain with a minimum of effort the location of the mortar from the information as presented to them.

TYPE OF RADAR: A pulsed radar system is essential to produce the range and accuracy required in this system. However, some form of MTI or Aural Doppler might well be added to the system, should other design characteristics (such as scan) permit.

PROPAGATION REQUIREMENTS AND MINIMUM RANGE:

It is required that the system be capable of detecting a mortar shell at 10,000 yards through rain.

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SECTION IV

PROPOSED MULTI-BEAM MORTAR LOCATION SYSTEM

76. The information contained in Sections I, II and III indicate that a system such as the following might best solve the mortar location problem.

SYSTEM SPECIFICATIONS

77. The following tentative specifications were adopted for the proposed radar:

(a) Transmitter Frequency: 2000 megacycles
(b) Radar Accuracy: approximately ± 25 yards in range and ± 8 mils in angle (with automatic range tracking and continuous angle information).
(c) Type of Scan: electronic discrete sector scan
(d) Type of Presentation: A-scope, expanded A-scope for range discrimination and accurate pip matching, and three phase azimuth indicator; to be operated by two men.
(e) Type of Radar: pulsed radar with MTI
(f) Maximum Range: 10,000 yards at all shell aspects through moderately heavy rain. (Figure obtained by comparison with field test data on existing systems.)
(g) Peak Power: approximately 100 KW (Average Power: approximately 300 watts)
(h) Pulse length: 1/2 microsecond (corresponding to a range discrimination of less than 100 yards)
(i) Vertical Beam Width: 5°
(j) Vertical Beam Separation: 2°
(k) Horizontal Beam Width: 12°
(l) Horizontal Beam Separation: 9°
(m) Antenna: ellipsoidal lens
    1. major axis approximately 7 feet, in the vertical plane
    2. minor axis approximately 3 feet, in the horiztontal plane
(n) Pulse Repetition Rate: 6000 pps. Effectively 1000 pps. per beam position

78. Operating Characteristics:

(a) Control area: 30° in azimuth by 10,000 yards (or more) in range. It will be possible to vary this sector as desired at a rate limited primarily by the efficient operation of the MTI.

(b) Traffic: The equipment will handle a maximum of three shells per minute or 180 sites located per hour if three men are used; two shells per minute or 120 sites per hour if two men are used.

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(c) Selectivity:

1. for similar classes of objects, e.g. other shells, aircraft, etc., in general selectivity would be obtained by range discrimination, or if necessary by noting the target behavior as presented on the tracer.

2. for dissimilar classes of objects, e.g. land clutter and very slow moving targets, selectivity would be obtained through the use of MTI.

(d) Physical Demands: The weight of the system would be in the neighborhood of 1500 pounds or less, providing sufficient stress is placed on engineering for light weight and use is made of modern light-weight components. A light weight system, in general, can be easily made mobile as required.

DESCRIPTION OF THE SYSTEM

79. Antenna Unit: The antenna of the proposed system consists of six feeds and an ellipsodial lens with a 7 foot major axis in the vertical plane and a 3 foot minor axis in the horizontal plane. The six feeds produce six beams (see Plate IV), an upper and a lower beam at each of three azimuth beam positions. The azimuth width of each beam is 12°, and the separation between the axis of these beams is 9°. This produces a 30° coverage between half power contours in azimuth, and two azimuth croos-over points at approximately the .8 power contour. The vertical width of each beam is 5°, and the separation between the axis of these beams is 2°. This produces a vertical coverage of 7° and one vertical cross-over point at approximately the .85 power contour.

80. Electronic Operation: (See Plate IV for a simplified block diagram of the system.) The basic timing reference of the radar may involve the mercury delay line if used. The modulator is triggered by the keyer pulse from the delay line. Pulse 1 is switched by the transmitter switch to feed 1 which corresponds to beam position a_{lower}. Pulse 2 is switched to feed 2, beam a_{upper}. Pulse 3 is switched to feed 3, beam b_{ℓ}. Pulse 4 is switched to feed 4, beam c_u. Pulse 7 is switched to feed 1, beam a_{ℓ}, and the cycle repeats. Since the p.r.f. = 6000 pps. then the effective pulses per beam position per sec. = 1000. The energy received by feed 1 is that reflected from the energy transmitted in pulse 1, beam a_{ℓ} and so on. All the energy received passes back through the same T.R. box and receiver. This is possible since discrimination with respect to beam position is determined by the position of the pulse in the cycle and occurs at a later stage. The response of the receiver should be reasonably linear. The returned energy is amplified in the receiver and fed into the MTI circuits. Part of the received energy passes through the delay line and part of the energy proceeds to the mixer where stationary targets are cancelled out as follows: The delayed energy from pulse 1 is cancelled out by

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the energy from pulse 7, since both these pulses correspond to the same beam position, and pulse 1 is delayed exactly $\frac{6}{\text{p.r.f.}}$ seconds ($\doteq$ 1 millisecond). The length of the delay line is thus equivalent to that of a simple 1000 p.r.f. system. The resultant energy from the MTI mixer is fed into a receiver switch which is synched with the transmitter switch, and switches the energy corresponding to pulse 1 into channel 1; pulse 2 into channel 2, etc. The energy received from pulses 1, 3 and 5 is applied to the lower plate of the search-range scope. The energy in each of these three channels is isolated by buffers as shown. The energy received from pulses 2, 4, and 6 in like manner is applied to the upper plate of the search-range scope, etc. A gated portion of the search-range scope is also applied to the fire control range scope. (See Plate V). The energy received from pulses 1 and 2, isolated by buffers as shown is passed through an integrator and applied to the left plate of the azimuth scope. (Plate IV). The energy from pulses 3 and 4, isolated by buffers, is likewise passed through an integrator and applied to the upper plate of the azimuth scope. The energy from pulses 5 and 6 is applied to the right hand plate of the azimuth scope.

81. <u>Physical Operation</u>: A description of the process of the detection of a mortar shell will now best explain the fundamental principles of the system. If a mortar fires in the control area of the radar (30° in azimuth by 10,000 yards) an indication will appear on the search scope in the form of an envelope, large at first, then diminishing until the magnitude of the envelope balances as the shell passes through the cross-over point of the upper and lower beams. During this period operator 1 (at the search-elevation position - see Plate V) will move a range gate of variable width out to the target echo. The presentation in this range gate will appear at right on the fire control scope, whose range display equals the width of the gate. Good range discrimination is achieved in this fashion. Operator 1 locks the gate on the target and initiates automatic range tracking. Operators 1 and 2 then commence to track the mortar shell manually. Operator 1 matches the magnitude of the upper and lower envelope of target echo on the fire control scope, thus causing the antenna to mechanically follow the elevation variation of the mortar shell. The azimuth scope indicates the variation in azimuth of the shell for only the target gated by operator. This is done by matching the returned power in the three sectors corresponding to the three azimuth beam positions on the plates of the scope. Since the sweep on the scope will rotate in proportion to the voltage on the scope plates, an azimuth position is obtained. This is a new method and presents some complications. Should it not be practicable it would be possible to use the returned information to manually track in azimuth, matching the target strength at either of the two azimuth cross-over points. In the former case Operator 2 would need to change the main azimuth dial only for sector search greater than 30° or in order to keep the shell in the radar beam as it changed its azimuth. The main azimuth control (Plate V) rotates the whole antenna assembly. The vernier azimuth control rotates mechanically or otherwise, a marker which when superimposed on the sweep of the scope indicates the azimuth of the target. Thus a combination of the two informations given

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above gives the actual azimuth position of the mortar shell. In the latter method both controls would again be used, but the vernier control would have essentially only two positions, representing the azimuth cross-over points. The main azimuth control would then be used to match the indication on the scope with the closer of the two vernier positions.

82. Tracer: Finally, a three-pen tracer system similar to the RC-308 used in conjunction with the SCR-584 for mortar location would be built into the indicator cabinet. (See Plate V). The three pens shown vary only up and down, and all may utilize the whole scale, being displaced to permit this. A sheet of paper rotates under the pens at constant rate. Pen 1 is proportional to azimuth, pen 2 to range, and pen 3 to elevation. The scale divisions are arbitrary. Pen 3 traces out a section of a parabola. Since this parabola shows elevation angle versus a constant time, a single uniform parabola may be used to extrapolate the section of the parabola to the time (t_o) of the origination of the mortar shell. This point will be determined by the point of interesection of the parabola with the height of the terrain in the region of the mortar. With t_o given, the azimuth and range indications may be extrapolated back to t_o^o and the range and azimuth of the mortar site read immediately. This whole operation should not take more than thirty seconds for the two operators mentioned.

DISCUSSION OF THE SYSTEM

83. Problems of the System: There are three major problems of this system: (a) the development of a method for switching the transmitter power, (b) the development of satisfactory circuits for the comparison of energy to utilize the first method suggested for obtaining azimuth positions, and (c) the light weight, rugged engineering of the system. A model switch for X-band capable of switching transmitter power up to 50 KW at a rate of 8000 times per second with less than one db. loss has been developed by Sylvania Electric Products and could probably be scaled to the requirements listed above. It is at least theoretically possible to solve problem (b), and practically, sufficiently feasible to warrant development. Good engineering and full utilization of lightweight components and material can solve problem (c).

84. Some Design Considerations: The information given in the body of the report which leads to placing the frequency of the mortar system in the region between S-band and L-band was: (a) that operation of existing systems on frequencies above S-band through rain had been found to be unsatisfactory, and no satisfactory method had been found for overcoming these effects, (b) that operation through rain on L-band (25 cm) had been found satisfactory with existing systems against mortars, (c) that design considerations imply that the frequencies should be as high as possible consistent with (a) above, and (d) the mortar shell aspect becomes a critical factor above S-band. A consideration of electromagnetic propagation through rain suggests that a wavelength of 15 cm could be used for operation through rain. To guarantee that a wavelength of 15 cm be satisfactory would require additional information.

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In addition, methods of discriminating against back-scattering from rain on 10 cm should be investigated, since this wavelength presents several advantages over 15 cm. Having fixed the radar frequency in the region below S-band, in any case, certain conclusions necessarily follow regarding a system design.

i. Continuous information operation is the only means of meeting the accuracy requirements.

ii. No sharp beam forming method for obtaining continuous information is permissible.

iii. From (ii) and from the fact that at 10,000 yards in a normal mortar trajectory a mortar shell at maximum height subtends an angle of about 3° at the radar, MTI is necessary to make the radar essentially independent of its site.

iv. But from (i) and (ii) some form of automatic tracking, not dependent on very sharp beams, must be used. (iii) precludes the use of conical scan or other methods for fire control operations and, of course, rapid sector scan for target acquisition.

v. It is seen that a discrete sector scan for target acquisition and fire control operations is necessary.

85. Merits of the System: To clarify the advantages of this system, consider the present two best possibilities for mortar locators, the SCR-584 and the AN/TPQ-2. The SCR-584 is unsatisfactory because: (a) it is too large (about ten tons), (b) it must scan for fire control information, (c) its angle control area is inadequate (approximately equal to the antenna beam width, i.e. 6°), (d) the traffic handling capacity is uncertain, and mortar site location is dependent on at least one shell being fired by the mortar and locked on after one previous shell has been detected. The AN/TPQ-2 is unsatisfactory because (a) the range on mortar shells is inadequate (about 5000 yards) on poor aspects, (b) operation through even light rain is impossible, (c) target acquisition is obtained through a complex mechanical sector scan. The multi-beam system for location of mortars described here will (a) be lightweight, (b) have a control area of 30° within which any one shell fired will be detected and sufficient information obtained from this shell to locate the mortar site within the accuracy for effective counter-fire, (c) possess MTI, thus suiting the system ideally for the role of road sentinel or the detection of low-flying aircraft, (d) possess the requisite sensitivity, independent of weather conditions or shell aspect, (e) satisfactorily meet the other requirements as described in Section III of this report. In addition, the time allotted for the development and production of a mortar location radar as indicated in the body of this report (about 1948) is sufficient for the system described here.

ACKNOWLEDGEMENTS

86. An acknowledgement is made to Major C. L. Parody, U.S.M.C.R., Marine Corps Radar Design Section, Bureau of Ships; Major E. Witting, U.S.A.S.C., Army Liaison Officer, Naval Research Laboratory; and Lt. (jg) E. W. Fischer, U.S.N.R., Electronic Special Research Division, Naval

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Research Laboratory, for the assistance they have given the author in preparing this report. The idea contained in the proposed mortar location system arose from numerous discussions with members of the Naval Research Laboratory and those institutions mentioned in Appendix I.

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29. Test 2, Report of Trials of Radar Sets SCR-584 and AN/TPS-3
30. Test 3, Tests of Radar Sets SCR-584 and AN/TPS-3 for Mortar Location Confusion Conditions - Ft. Sill Memo for file to OCSigO
31. Test 4, Tests of Radar Sets SCR-584 and AN/TPS-3 for Adjustment of Fire - Ft. Sill Memo for file to OCSigO
32. Test 5, Tests of Radar Sets SCR-584 and AN/TPS-3 for Locating Enemy Artillery - Ft. Sill Memo to file to OCSigO
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68. The Mathematics of the Location of Mortar Sites by Radar - NRL Report R-2823
69. Australian Council of Scientific and Industrial Research - The Ultimate Visibility of Signals on a PPI Display and the Effect of Electrical Parameters on Visibility - RP 252/1
70. Australian Council of Scientific and Industrial Research - Charts for the Calculation of the Smallest Signal Visible on a PPI Display - RP-252/2

[redacted]

APPENDIX I

Sources of Information

A. For the compilation of the bibliography of this report and in order to permit the study of undistributed memorandum, correspondence and other documents, the following files were made available:

1. Naval Research Laboratory
   Anacostia Station
   Washington 20, D. C.

2. Chief of the Bureau of Ships
   Navy Department
   Washington 25, D. C.

3. Chief of the Bureau of Ordnance
   Navy Department
   Washington 25, D. C.

4. Chief of Naval Operations
   Operational Research Group
   Navy Department
   Washington 25, D. C.

5. Commander-in-Chief, U.S. Fleet
   Navy Department
   Washington 25, D.C.
   Attn: Section F-49

6. Chief Signal Officer
   Room 4D235, Pentagon Bldg.,
   Washington 25, D.C.

7. Ordnance Branch, USA
   Pentagon Building
   Washington 25, D.C.

8. Camp Evans Signal Laboratory
   Belmar, N.J.

B. Conferences were held with the following organizations through the personnel listed.

1. Place

   Sperry Gyroscope Co., Inc.
   Research Laboratory
   Garden City, L.I., N.Y.

[redacted]

Representatives

1. E. J. Barlow
2. W. L. Barrow

Date

January 9, 1946
January 31, 1946

2. Place

Bell Telephone Laboratories
Murray Hill,
New Jersey

Representatives

1. W. P. Mason
2. H. J. McSkimin

Date

7 January 1946

3. Place

Bell Telephone Laboratories
180 Varick St.
New York, N. Y.

Representatives

1. R. S. Caruthers
2. R. Hough

Date

19 December 1945
8 January 1946

4. Place

Bureau of Ships, Code 919
Marine Corps Design Section
Navy Department
Washington 25, D. C.

[redacted]

Representative

1. Capt. C. L. Parody, USMCR, Code 939B, Project Engineer
2. Lt. Col. Ramsey, USMCR, Code 919(903)

Date

27 August 1945

5. Place

Director of Artillery
National Defense Headquarters
Ottawa, Canada

Representatives

1. Lt. Col. C. A. Ranson, Director
2. Major C. H. Jervis - Read.

Date

7 December 1945

6. Place

Camp Evans Signal Laboratory
Belmar, N. J.

Representatives

1. J. T. Evers
2. E. K. Stodola

Date

5 November 1945
6 November 1945
29 August 1945

7. Place

Applied Physics Laboratory
Silver Springs, Md.

Representatives

1. Major J. T. Massey
2. Henry Porter

[redacted]

Date

28 November 1945

8. Place

Marine Corps Station
Quantico, Va.

Representatives

1. Capt. Lambert

Date

26 November 1945

9. Place

Wright Field, AAF
Air Technical Command,
Dayton, Ohio

Representatives

1. Capt. A. B. Meier
2. Dr. Bennet

Date

2 November 1945

10. Place

Robinson Laboratory
Ohio State Universtiy
Columbus, Ohio

Representative

1. Dr. K. P. Yates

Date

19 October 1945

11. Place

Radiation Laboratory, MIT
Boston, Mass.

[redacted]

Representatives

1. Leo Sullivan
2. H. R. Worthington

Date

31 August 1945

12. Place

Bureau of Ordnance, Re4f
Navy Department
Washington 25, D. C.

Representatives

1. Lt. Comdr. Bridges
2. Lt. Comdr. B/ I. Valentine

Date

11 September 1945

13. Place

U. S. Atlantic Fleet Operational
Training Command, (COTCLant)

Representative

1. Lt. Comdr. Mathews

Date

24 & 25 August 1945

14. Place

U. S. Naval Proving Grounds
Dahlgren, Va.

Representatives

1. Lt. S. C. Liscombe
2. Lt. W. J. Sutton

Date

6 August 1945

[redacted]

15. Place

Radar Research and Development Establishment
Representing Great Britain
1800 K St., N. W.
Washington, D. C.

Representatives

1. Major Hoskins
2. G. B. Parkinson

Date

23 October 1945

16. Place

Ordnance Branch, USA
Pentagon Building
Washington 25, D. C.

Representative

1. Major Ransome

Date

October 1945

C. Activities at which the author has been a consultant:

1. Field tests against mortars the week of 6 August 1945 at CBA.

(a) Mortar Location by Fire Control Radar, BuOrd Problem O-176R-S (See NRL Report R-2653)

(b) Memo from R. Crane to J. P. Hagen, 8 August 1945, "Radar Research Mortar Location by the SG-1, SO-3, SU, SP, SM, and SO-7M at CBA.

2. Field tests against mortars, 6 August 1945 at Dahlgren, Va. (See conference report S-390-327/45, 6 August 1945, "Use and Operation of Mk 8 Mod 3 in Detecting Mortar Shells in Flight and Locating the Mortar Position" - performed at the Naval Proving Grounds, Dahlgren, in conjunction with Re4f, BuOrd).

3. Field tests against mortars, 9 August 1945 through 14 August 1945 at Ft. Pierce, Fla.

(a) See "Radar Detection of Mortar Fire Tests" report of 24 August 1945 by U.S. Atlantic Fleet Operational Training Command.

(b) Conference report serial C-390-359/45, 9 August 1945 through 14 August 1945, "Mortar Location by Shipborne Radar" (Mk 22 Mod 2, Mk 12, SG-1).

4. Field tests against mortars at Casco Bay, Main, on 7 September 1945.

(a) See report from Commander Operational Development Force, U.S. Fleet on "Detection of Mortar Fire by Shipborne Radar - Report of Tests" (Mk 8 Mod 3, Mk 13, SG, SG/MTI, SP, Mk 13-1, Mk 29-2)

(b) Memo from R. Crane to Lt. Comdr. Valentine, 5 September 1945, "Report on Tests on SP (with 8' dish) Aboard DD LEARY at Sea Island".

[redacted]

TABLE I

RADAR RANGES AGAINST 81 mm MORTAR SHELLS

U. S. RADARS

Radar	Range Yards	Shell Aspect
SCR-584	7000	poor
	8500	good
AN/TPQ-3 (Mod. TPS-3)	12000	good
AN/PPS-1	800	good
AN/TPS-1A	10000	poor
	11000	good
AN/TPS-2	12000	poor
	12000	good
AN/TPS-5	2500	good
602-T5	25000	good
SCR-517	3000	good
AN/TPL-1	5000	good
AN/TPQ-2	5000	good
AN/APG-16	negative	
AN/APQ-4 (Mod. APS-3)	3500	good
AN/APS-4	negative	
SCR-720	2500	good
"Whirling Dervish"	6000	good
Mk 8 Mod 0, 1, 2	2000	good
Mk 8 Mod 3	5000	good
Mk 12	12000	good
Mk 12	5000	good
Mk 20 Mod 1	4000	good
SG-1 b, e	9000	good
SP	20000	good
SO-3	3000	good
SU	4000	good
SO-12M	10000	good
SO-7M	12000	good
Mk 20 Mod 1, 2	6000	good

U.K. RADARS

Radar	Range Yards	Shell Aspect
GL 111B	8000	good
CA #1 Mk IV	4000	good
"Watchdog"	1000	good
A.A. #3 Mk II	8000	good
A.A. #4 Mk III	17000	good
Type 931	4000	good
Canadian K-Band (Experimental)	6000	good

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TABLE II

RADAR CHARACTERISTICS

	AN/TPQ-2	Canadian K-Band	Norman	Whirling Dervish
Frequency (Mc)	24,000	26,000	3000	10,000
Peak Power (Kw)	20	20		50
Beam Width (°)	1 x 1	1 x 1	3 x 3	1.5 x 1.5
Beam Position	See Plate 3	See Plate 3	See Plate 2	See Plate 3
Scan	20° Sector	10° Sector	90° Sector	90° Sector
Scan Method	"Lewis"	"Foster"	Rotating Duo-dish	Rotating Duo-dish
Scan Speed (°/sec)	600	300	90	180
Pulse Width (μs)	.1	.1	1	.5
Presentation	B	B	PPI	B
Computing Method	Electrical	Slide Rule	Direct Reading	Slide Rule
Approximate Weight (lbs)	3000	1500	3000	5000

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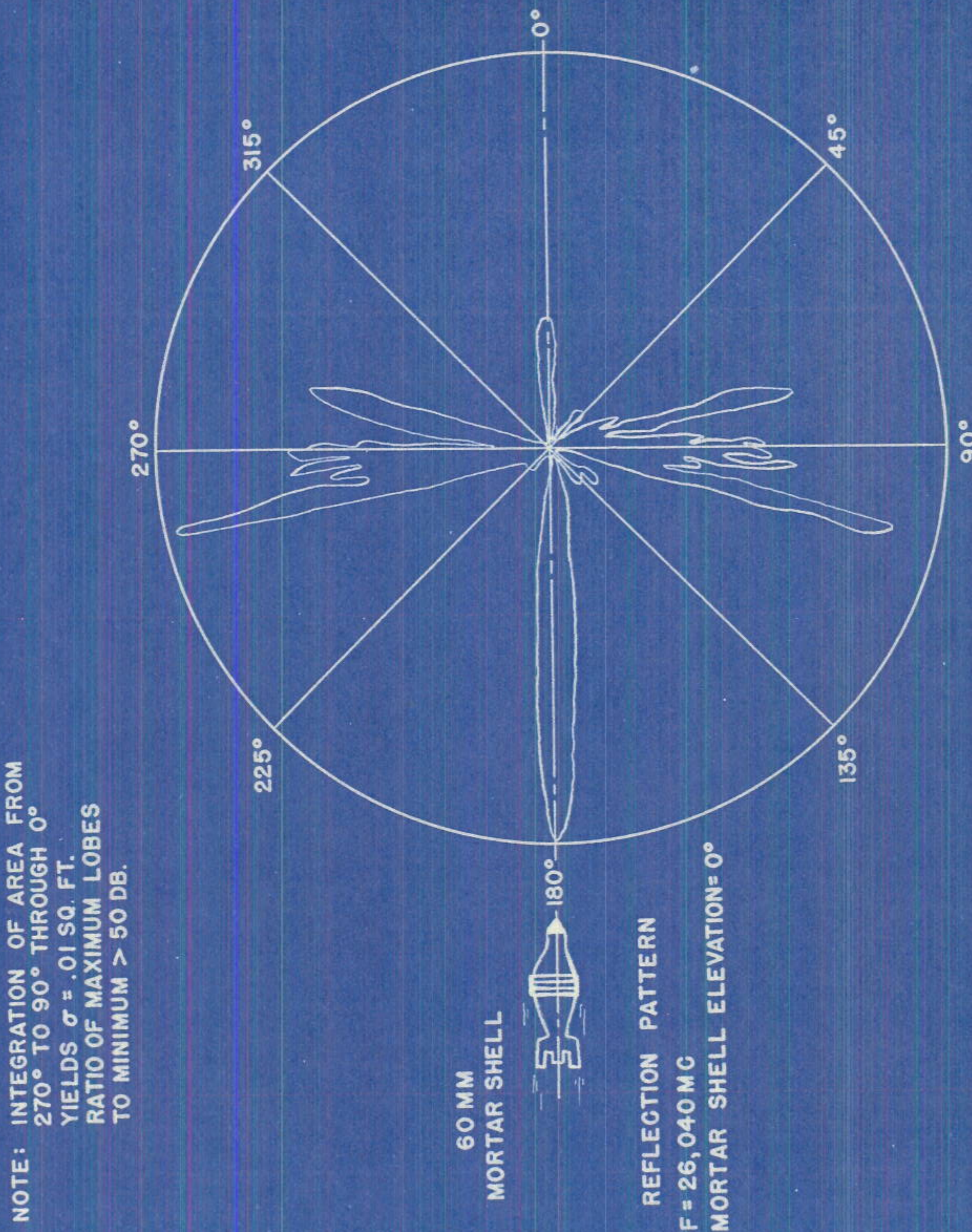
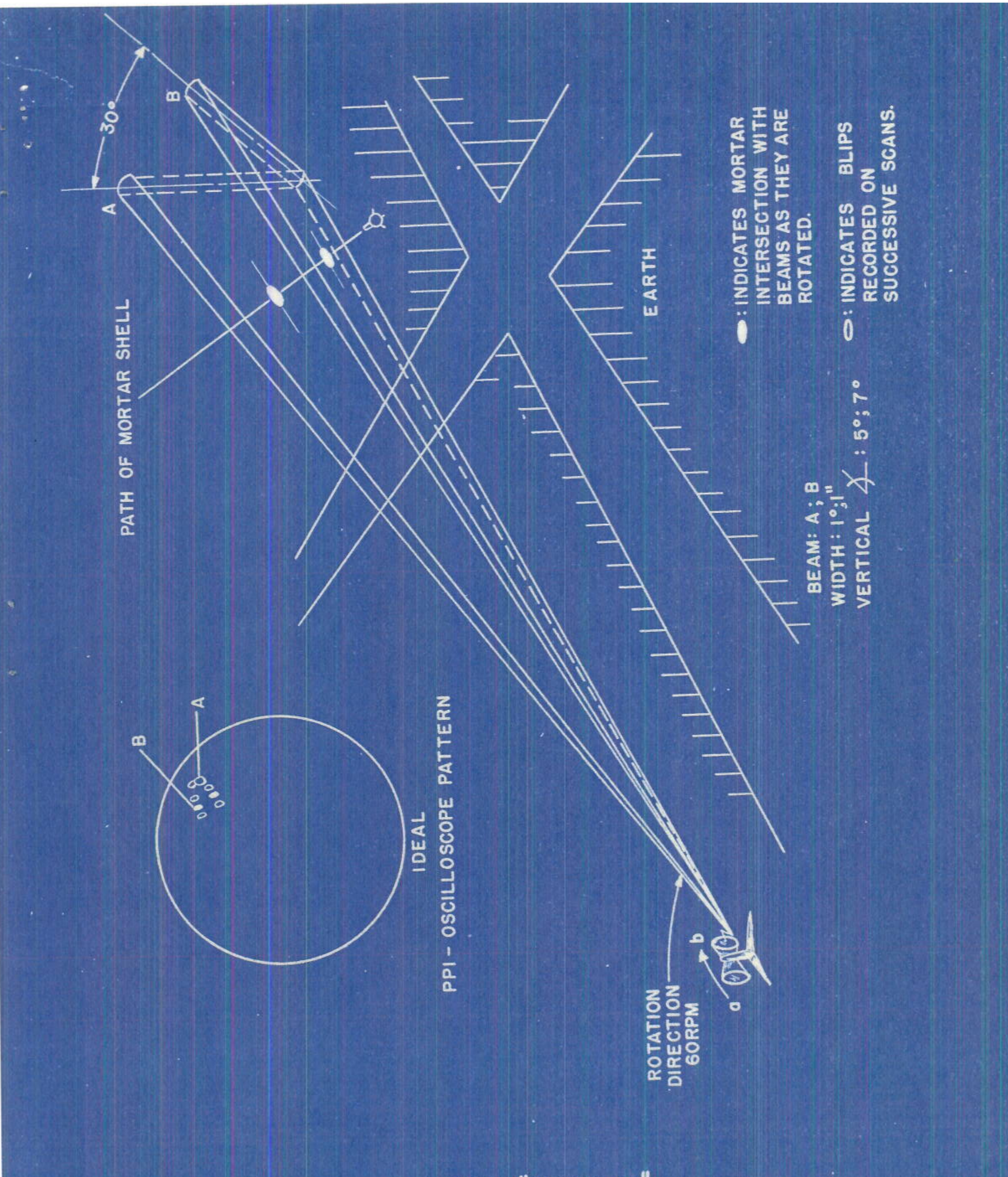
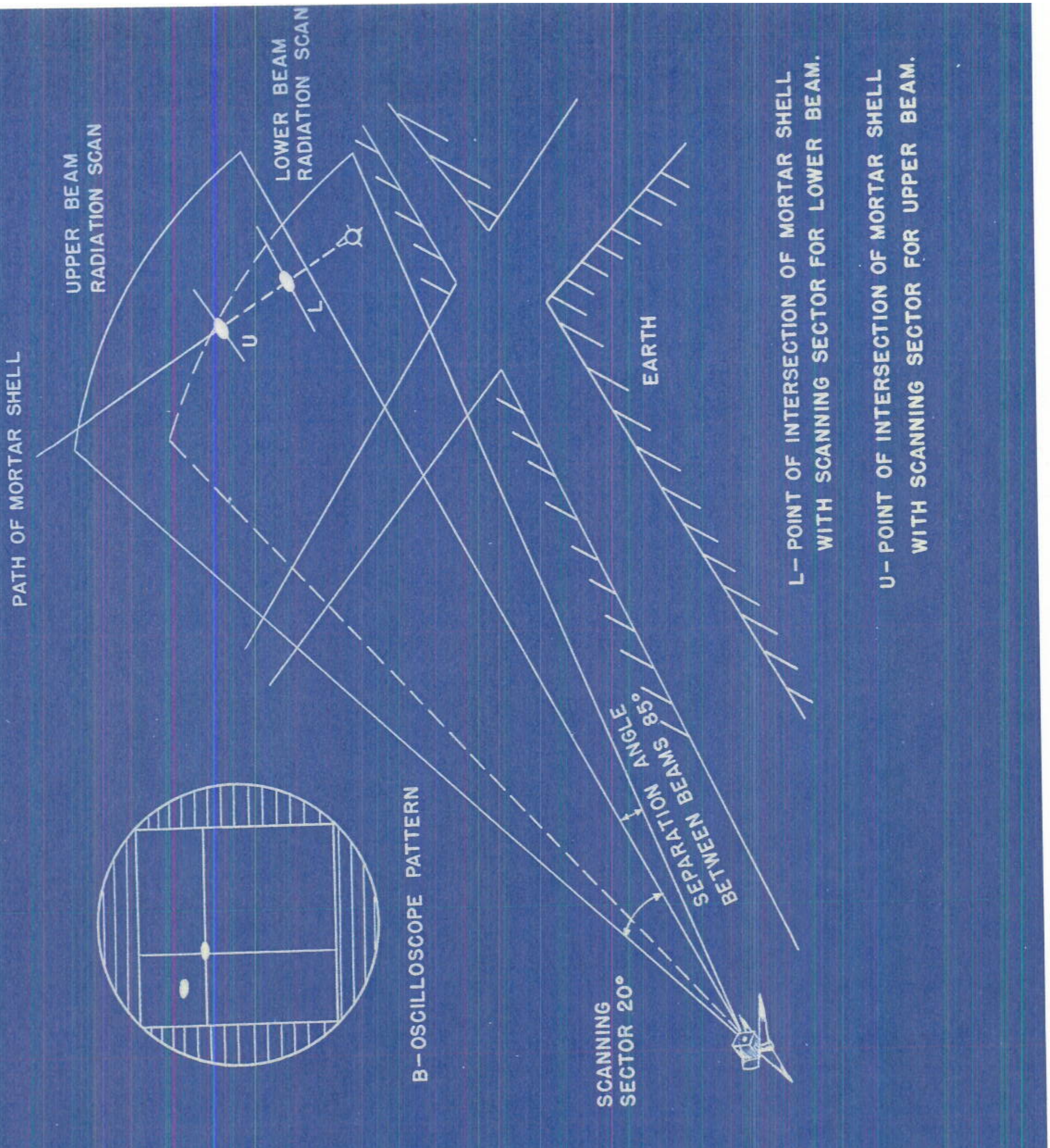


REFLECTION PATTERN OF 60MM
MORTAR SHELL ON K- BAND



SIMULATED "NORMAN"
RADIATION SCANNING SECTOR

DECLASSIFIED



AN/TPQ-2
RADIATION SCANNING SECTOR

DECLASSIFIED

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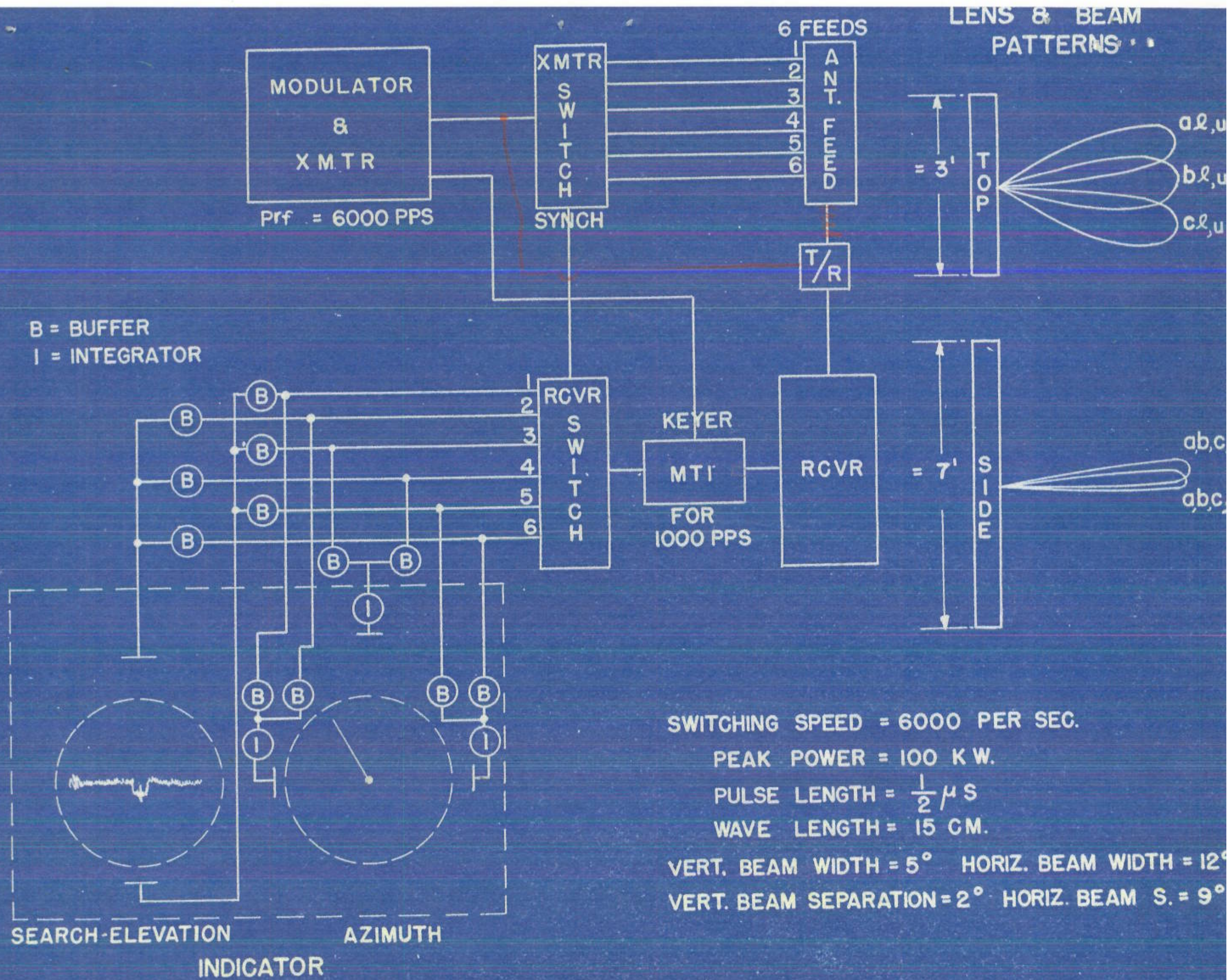

MULTI-BEAM METHOD OF LOCATING ENEMY MORTAR SITES