

# A PROPOSAL FOR AN OPERATIONAL HF RADAR

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## ABSTRACT AND SUMMARY

In response to the request of 7 March 1963 from the Director of Defense Research and Engineering a radar system is proposed for the primary purpose of surveillance and tracking of aircraft within the USSR and the secondary purpose of detection of missile and ESV launchings.

The radar system being proposed is based on the design of the Madre radar and the experience gained with the Madre installation at the NRL Chesapeake Bay Annex. The proposed radar, being required to meet perhaps the most severe demand which could be made of such a high frequency OTH radar, should have somewhat greater sensitivity, clutter rejection capability and frequency range (6 to 30 Mc) than the NRL Madre. It should also have complete flexibility of operating frequency choice and of antenna scan. These characteristics for the operational radar system are dictated by the combined effect of the information requirements desired and the environment within which the radar must perform, including such factors as the following:

- a. Coverage at all ranges from 500 naut. mi. to 2000 naut. mi. (The minimum range is the most difficult to obtain).
- b. Effective operation to as near 24 hours a day as practical (made especially severe during the current low period in the sunspot cycle which will continue for about 3 years).
- c. Concern over vulnerability to ECM, both jammer and repeater types.
- d. Flexibility of antenna scan both to allow increase in information rate and to provide a capability for missile and ESV launch detection.
- e. Provision for growth, at moderate relative cost, in the capability of the original installation in particular with respect to c and d above.

The possible, if not probable, characteristics of the proposed basic radar element are as follows:

Frequency -- 6 to 30 Mc changeable in one pulse interval.

Antenna -- array or arrays of wide band elements (log-periodic or flat spirals for example) -- 700 feet long and 150 feet high, feeding a common reflector. R2R circular array, also possible choice.

Beamwidth --  $2^{\circ}$  to  $10^{\circ}$  depending on frequency in use.

Gain -- 20 db at 14 Mc.

Scan -- phasing of array elements at inputs to multiple transmitter amplifiers -- change beam position in one pulse interval.

Transmitter -- multiple element distributed type broadband amplifiers fed from phasing matrix. 600 KW total average power, up to 10 MW peak.

Receiver/processor -- multiple RF/IF sections into beam forming matrix, special attention given to clutter rejection and dynamic range and choice of integration (dwell) time from less than 1 sec. up to 20 seconds.

The characteristics listed above represent a number of design steps significantly beyond that of the Madre system now at CBA. However, much applicable radar development work has been done in the past few years and all the techniques to be used may be considered state-of-the art, comparable in availability and development to essential parts of Madre itself such as the magnetic drum and processor equipment -- currently being improved.

The most severe design problems are presented by the antenna. Wide band radiators are on hand but their use in an array covering 6-30 Mc, or in 3 stacked arrays covering this range, has not been demonstrated to date.

Another question, which was resolved by extrapolation from Madre performance (lowest frequency 13.5 Mc) and general communication ionosphere data, is the efficacy of the system when ionosphere conditions require use of the lower frequencies -- 6 to 10 Mc.

The consideration given to siting is developed at length in the main sections of this report. The tentative choice is, for two stations, Prestwick, Scotland and Elazig, Turkey. Facilities available, coverage provided, and electronic isolation were all considered in this choice. For a single installation, the site in Turkey is preferred. However, should only a minimum single installation be planned the use of a shipborne system is recommended at least for further consideration.

Estimates of cost are included. The basic elemental radar, one capable of 60 degrees of azimuthal coverage, foreign installed is estimated to cost between 13 and 15 million dollars. Three systems at a site to provide 180 degrees coverage could cost about 2.5 times this. A single radar with 3 selectable antennas (each 60 degrees -- total 180 degrees) at one site is estimated at 1.5 times the basic system.

Under a tight schedule these radars can be installed in 18 to 24 months after contract.

It is pointed out that the complete requirements placed on this radar system are severe. The basic radar element (60 degrees coverage) to meet these requirements is comparable in size, sensitivity, data gathering capability and cost to one of the search radar components of the EMEWS system.

#### PROBLEM STATUS

This is an interim report on one phase of the problem; work is continuing on other phases.

#### AUTHORIZATION

NRL Problem R02-23  
Project RF 001-02-41-4007

## INTRODUCTION

DOD Memorandum, Log No. 63-1297 of March 7, 1963, addressed to Navy, Air Force, DIA and ARPA, expresses interest in NRL's research HF Madre radar which has demonstrated the feasibility of detecting aircraft and missiles at great distances over-the-horizon.

Navy, in coordination with DIA, ARPA and USAF, is requested to prepare a program, based on "over-the-horizon" studies and tests, for procurement, installation at overseas sites, operation, support and data analysis of a system with a primary objective of surveillance and tracking of Soviet aircraft over much of their land mass, and with secondary ability to conduct continued experiments on detection of missiles and ESV launchings.

A number of conferences were held by NRL representatives with principals of Air Force, DIA and ARPA. These conferences considered the Soviet land mass coverage problem from a number of sites. The discussions pointed out the vast difference between tracking capability and population counting and included the special technical interest of at least two sites with the possible flexibility of selecting one site where a basic element could be installed and subsequently augmented if the information obtained warranted expansion. For the latter purpose it was established that Russia east of the Urals could be of secondary consideration on a basic step.

This document is NRL's action for Navy in answer to the DOD directive. Its content has been discussed with the addressees who contributed information and assistance in special areas and categories, thus making the document as detailed and informative as possible.

Historical Background The work preceding radio detection and ranging, which was accomplished at the Naval Research Laboratory during the 20's, employed H.F. transmitters. Indeed much of the pioneer pulse radar work of the 30's at the same establishment employed H.F. transmitters. World War II saw the tremendous effort and accomplishments of microwave radars, with the end of the conflict reviving work at HF, because progress in it was substantially interrupted by the war.

The postwar interest in the use of HF was extremely long range detection in an area over-the-horizon which is not illuminated by microwave radars. The USAF in the period 1946-1949 under a contract with Raytheon, attempted among other efforts to detect V-2 launches at White Sands from South Dartmouth, Massachusetts, with a HF system. MIT, Lincoln Laboratory, under project Caterpillar (ground wave propagation) attempted detections over-the-horizon from the Boston area eastward; their studies under project Cricket were aimed at over-the-horizon detection using ionospheric refraction.

In 1949 NRL initiated a HF radar program to study cross correlation and bandwidth narrowing techniques. The results of this study brought forth NRL's "Music" research type radar which was placed in operation in 1954.

This radar was used to successfully determine the frequency and amplitude characteristics of backscatter and means were provided to remove the normal backscatter. Backscatter elimination, the element which plagued early users, was an advance in the art which allowed Music to detect aircraft at 180 miles without interference from the thousands of square miles it illuminated over-the-horizon. The Music facility, though only 50 KW peak power on a modest gain antenna, pioneered in the detection of small atomic explosions at Frenchman's Flats in 1957 as well as missile perturbations of the ionosphere caused by launches from Cape Canaveral during the same and subsequent period.

A 50 KW peak power Madre which incorporated the advantages of Music, but employed magnetic storage and provided a velocity-range display was placed in operation at NRL in 1958. This radar using a modest gain antenna, repeated the ability of Music on aircraft out to 180 miles and demonstrated a distinctive signature of the ionosphere perturbations caused by missiles launched from Cape Canaveral.

While the mentioned Madre equipment was in manufacture, NRL sought funding to provide a high power amplifier and suitable antenna facilities to attempt detection of aircraft over-the-horizon and missile targets at the same range as soon after launch as possible. Funding was provided by DOD emergency funding, Navy and Air Force. September 1961 saw the high power Madre installed at the Chesapeake Bay Annex of NRL and despite an uncertain state of readiness it was used in September and October 1961 to detect NRL's WV-2 (now EC-121K) aircraft at a maximum range of 1700 naut. mi. on a flight Patuxent to the Azores. This was the first over-the-horizon detection and range recognition of aircraft at extreme ranges, a result which has been repeated many times since at shorter and longer ranges. The British Zinnia project, CW-doppler equipment with narrow banding, had in about 1957 made a detection by means of doppler recognition of aircraft over-the-horizon.

Special mention should be made of the high power Madre's ability to detect missiles. Experience with the complex has demonstrated that there are three areas of altitude of a missile after launch which Madre has identified. The rocket driven missile echo has shown target cross section enhancement as it approaches the E layer with velocity information corresponding to the missile. Also the missile target between E and F layer (60 to 180 miles) shows more cross section enhancement and velocity information diffusion. The F layer perturbation, a target capable of being confused with many things, is very evident, but Madre's high power is not needed to detect this disturbance.

While Music, and now Madre, have been under evaluation, the HF over-the-horizon detection programs, which include many operatives, have been very active. These are not elaborated upon here because none are capable of detection of aircraft over-the-horizon. Their emphasis has been placed upon the ionosphere perturbation and target enhancement between E and F layer due to rocket exhausts.

Long range detection of aircraft and missiles is still part of the Madre evaluation program. During the period of operation, 1961 to date, considerable thought and action have been taken on Air Force, Navy and ARPA money to bring Madre nearer to an operational form by exploring means to separate approaching and receding targets, to increase dynamic range, improve vulnerability to countermeasures, and of augmenting the low altitude missile detection problem with acceleration detection by incorporating acceleration gates to replace or co-use with the velocity gates. In substance there are operational versions of Madre which are within the state of the art and which have considerable CCM abilities.

#### GENERAL CONSIDERATIONS

All Russia Coverage The Soviet Union, its satellites and contiguous associates cover a large land area.\* If one conceived of operating Madre type surveillance over this land mass, perhaps sixteen installations would be required, some of them situated in politically questionable locations and in unison not quite capable of covering all the square miles encompassed. This venture would be formidable if an aircraft population count as a function of time were made at each station with a view in mind of compiling statistics which at some future time would allow one to designate an overactive or underactive week, day, hours, etc. If one envisioned tracking information on each aircraft detected, the data handling at each station would be out of the simple computer category with perhaps the added requirement of exchange of information between stations and some master data handling center. The foregoing remarks refer to reasonably fast aircraft, those capable of say 100-200 knots or more ground speed.

Populated Russia Coverage The Russian coverage problem is less formidable if the most populated portion is made the central focus. With this in mind, radar units projected to cover a range 500 to 2000 naut. mi. were envisioned at Bodo and Stravanger, Norway; Prestwick, Scotland; Izmir, Trabzon and Erzincan in Turkey, and Tehran, Iran. This multiplicity of station sites complemented each other, for one is aware that a doppler radar having a lower limit of doppler response dictated by removal of the natural backscatter doppler, must have a double cone of blindness which exists at any range, where the angle of the cone is set by some lower limit of ground speed on courses roughly at right angles to the radar rays. It should also be pointed out that moving targets on radial courses to the radar are also undetectable if their ground speed is below say 100 knots.

The multiplicity of stations mentioned gives one a feel for adequate coverage but too redundant for initial approach. Bodo, Norway should be discarded because of its proximity to auroral activity, a natural obstacle which might reduce the station's usefulness to 50-70 percent. The three

\* Far eastern Russia might be monitored from West Pakistan, India, Luzon P.I. and Japan. Red China would be a bonus coverage from such sites.

stations in Turkey might well be served by one site, with the Iranian site possibility deferred to a future expansion when some remote missile site (Sary Shagan) and activity north and east of the Urals become pressing. The arc of seven supposed stations has now been reduced to two. One may examine the locations of Prestwick and eastern Turkey more carefully since the next step, one of the two, is to be considered by itself.

Reduction to two sites results in some loss in the land mass illuminated redundantly as shown by Fig. 1, where the 500, 1000, 1500 and 2000 naut. mi. crescents from Prestwick and near Erzincan, Turkey are set forth. From these stations the area of possible  $180^\circ$  illumination extends from Yugoslavia to 500 miles beyond Sary Shagan, the central portion illuminating quite well Russia west and south of the Urals.

Illumination Vs Detection The area illuminated is one consideration, the most important consideration is the loss of detection of moving targets on some flight paths in this area. Figure 2 shows Prestwick (PK) and Erzincan (RZ) with the double cone of doppler silence shown at a selected range for three directions. If a Madre radar is arranged to detect moving targets that have a speed in excess of 100 knots in a direction radial to the radar, it will be found that 300 knot flight paths emanating from the cone origins or passing angularly within the cones will not be detected. The dotted double cones are for the Erzincan area; the solid ones from Prestwick. Flight speed higher than 300 knots would contract the angle of the cones; slower speed targets would increase the angle. These blind cones should be considered to be active independent of range. Figure 2 shows the center and right hand cone pairs from each station complementing each other by covering each others blind cone. The coincident cones on the direct line between (PK) and (RZ) show that both stations are blind simultaneously at all ranges if a moving target were to take off or fly through the enclosed cone areas at the proper angle.

Figure 2 examples the respective station complementary double cones at right angles in the vicinity of Moscow; double blindness exists over the Carpathian Mountains in the vicinity of Poznan, Poland; the situation for Russia immediately west of the Urals would not be much different from that shown for Moscow. Thus, this illustrates the nature of unavailable data as the number of sites are reduced. If it became necessary to be interested in the Carpathian Mountain area or anywhere on the line PK-RZ for flights in the direction of the cone azimuths, one would have to postulate a station in say Tunisia to remedy the situation.

Consider some representative flights. Figure 3 is plotted minimum detectable radial velocity vs. great circle distance on a flight Moscow to Minsk. The station at Erzincan (dotted line) for all practical purposes would not see much of this aircraft while Prestwick, the solid line, would see any moving targets over 130 knots ground speed.



Figure 1 - Range and azimuth from Prestwick, Scotland and near Erzincan

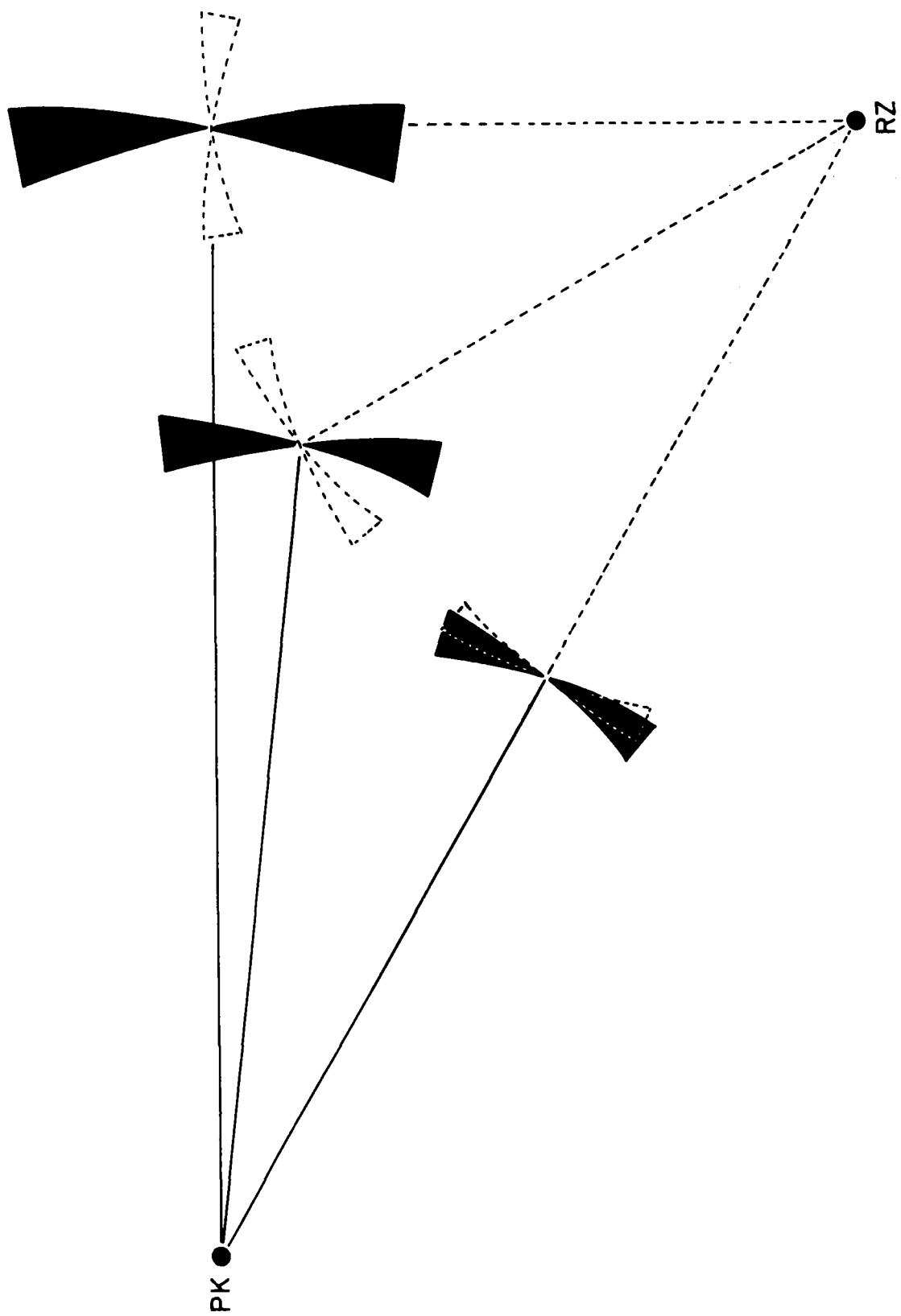


Figure 2 - Doppler radar blind cones from Erzincan

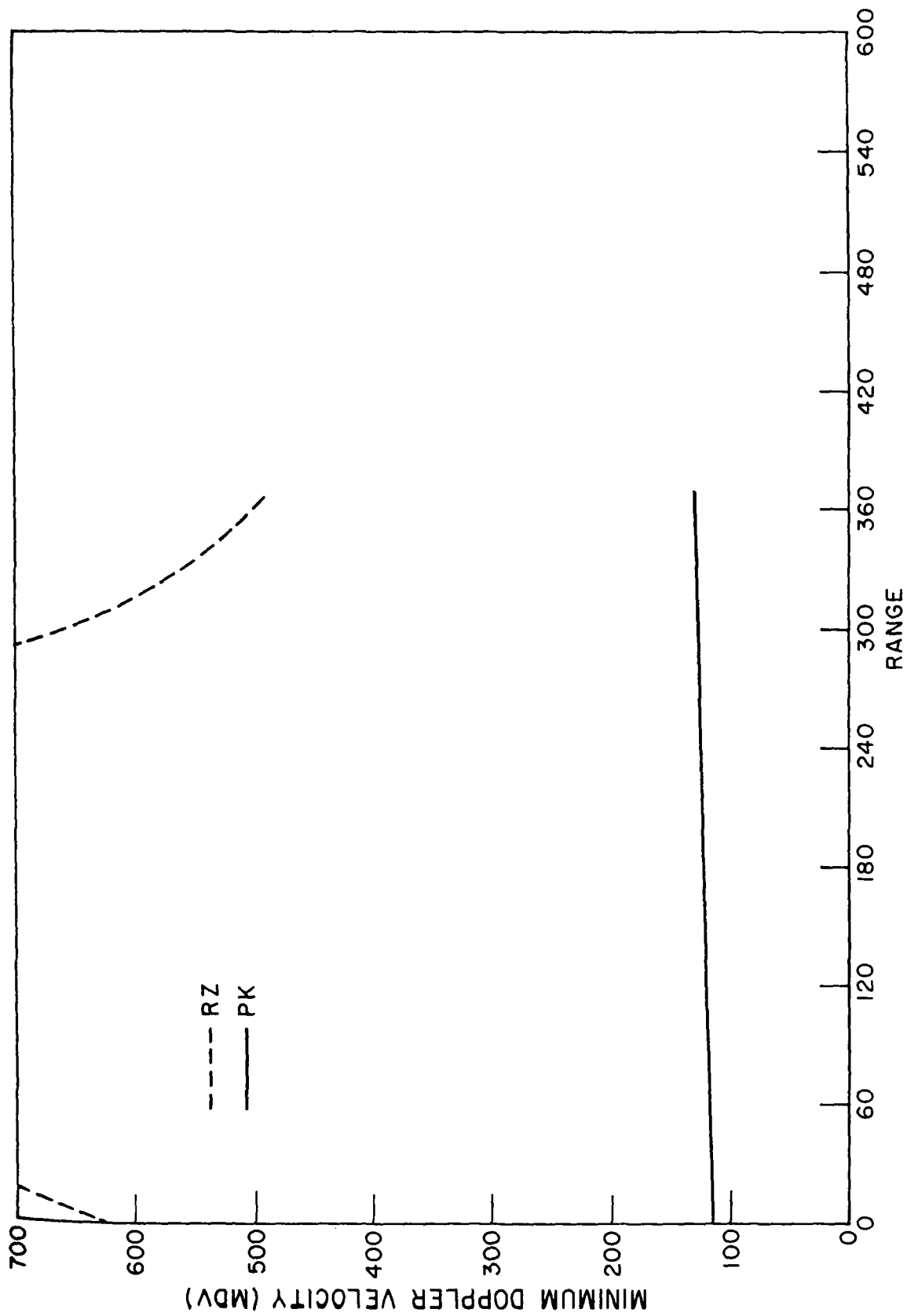


Figure 3 - Minimum doppler velocity, Moscow to Minsk

Figure 4 is a plot of minimum detectable radial velocity on a great circle path (Moscow to Leningrad) vs. great circle distance. The dotted and solid lines have the same meaning as before. It is clear that both stations could detect moving targets with speeds in excess of about 140 knots. This flight path is also close to the great circle path Moscow to Washington.

Figure 5 shows the same coordinates for a flight Moscow to Archangel. Here the solid line shows (PK) at a disadvantage whereas (RZ) Erzincan would see all moving targets above 110 knots. Figure 6, depicting the same coordinates, is for a flight Moscow to Stryy. For about half the path Prestwick would see moving targets under 200 knots with the other half restricted variably from 200 to 400 knots, whereas Erzincan (RZ) would be at a disadvantage. This example illustrates a flight which neither station could see to full advantage.

The desirable azimuth coverage from Prestwick is 60 degrees; that from Erzincan about 180 degrees. It is envisioned that these azimuth sectors be covered by a positionable radiating beam of say 8 - 10 degrees at mid-frequency and each beam projected to cover range from say 500 to 2000 naut. mi., with two to three operating frequencies in the minimum. It would require a redundancy of antennas (3) to cover three 60° sectors; with 60° the very upper limit due to a reduction of main lobe gain and severe side lobe problems at large steering angles for some designs.

Limited Site Coverage Prestwick Vs Eastern Turkey If one were to choose between Prestwick and near Erzincan as a one station starting point to acquire knowledge, the Erzincan area, though more costly, is in a position to expand and pick up some missile information which is beyond the range of Prestwick. Prestwick must look at a portion of busy Europe where frequency band occupancy is exceptionally high; an eastern Turkey location should be partially free from such in some sectors. Prestwick, on an east-west path, would have the customary sunrise disturbance for a longer period than a Turkish station's north-south look. Also the Turkish location can operate best in north-south coverage of some preferred flight patterns and is deemed desirable over Prestwick's generally east-west pattern, though Prestwick is in excellent position for Moscow - Tashkent, etc., traffic.

Turkish Site An eastern Turkey site, one close to Elazig is reasonable and recommended. See Pg. 14. There is an existing railroad, an important consideration for the movement of some material. This choice has a potential 180° coverage with three antennas where the central sector has adequate coverage of the various Soviet AICBM and missile launching sites, with special effectiveness on moving targets to or from the Soviet north coast. From this site's central sector it is possible to illuminate all Soviet Russia west of the Urals except a small section along the Black Sea.

A still further compromise should be considered, one that would be economical and not hinder subsequent data rate expansion. This involves

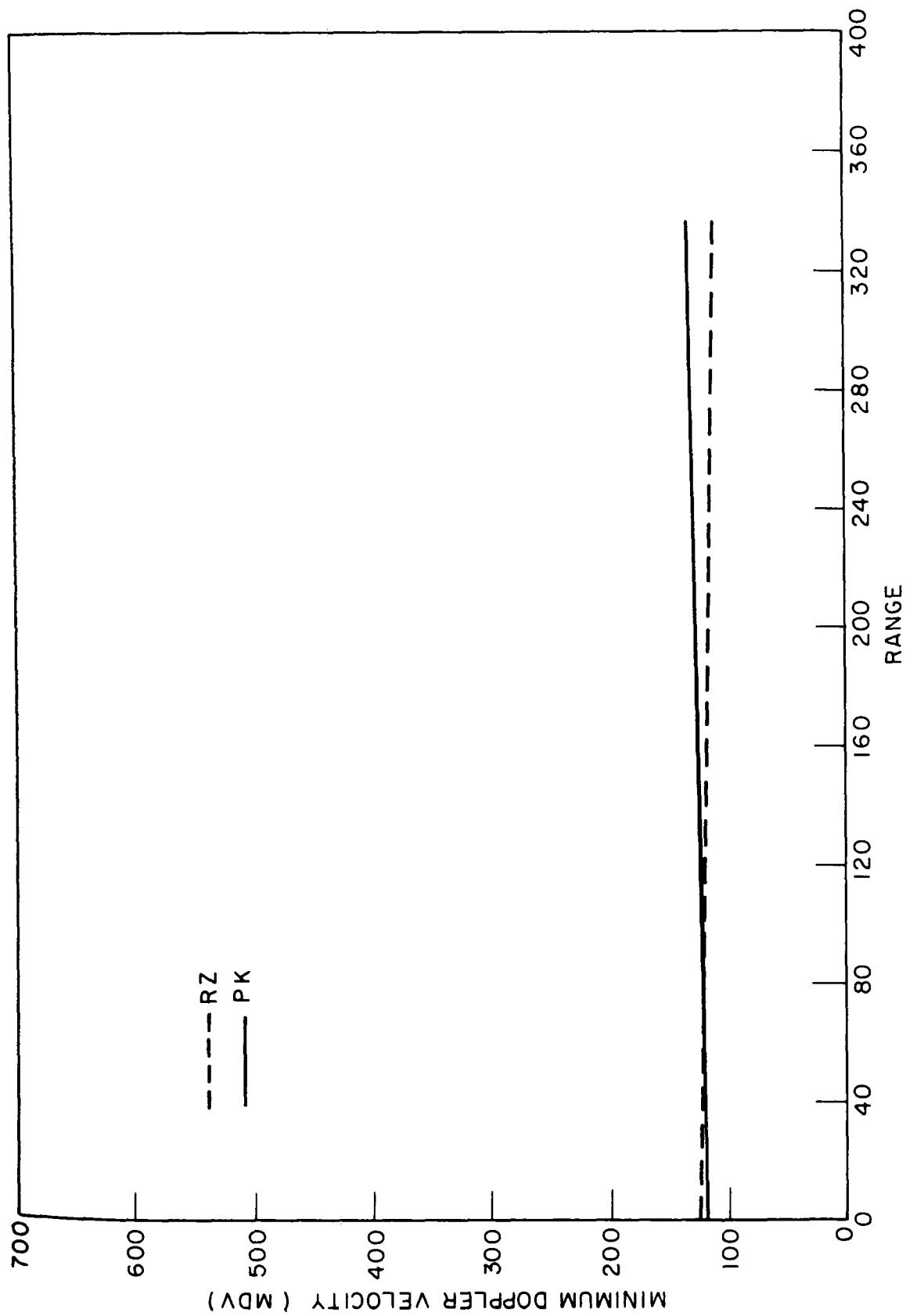


Figure 4 - Minimum doppler velocity, Moscow to Leningrad

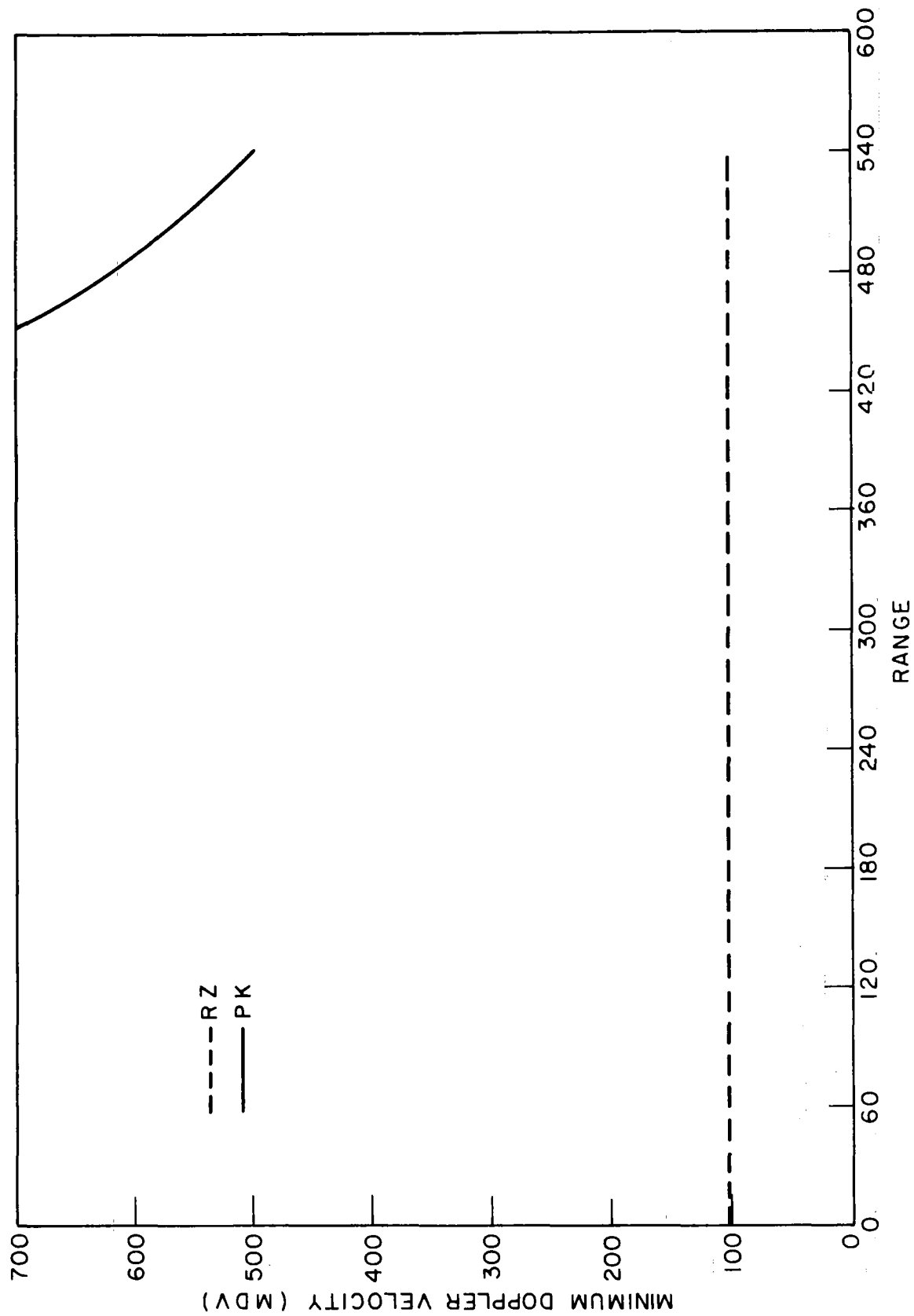


Figure 5 - Minimum doppler velocity, Moscow to Archangel

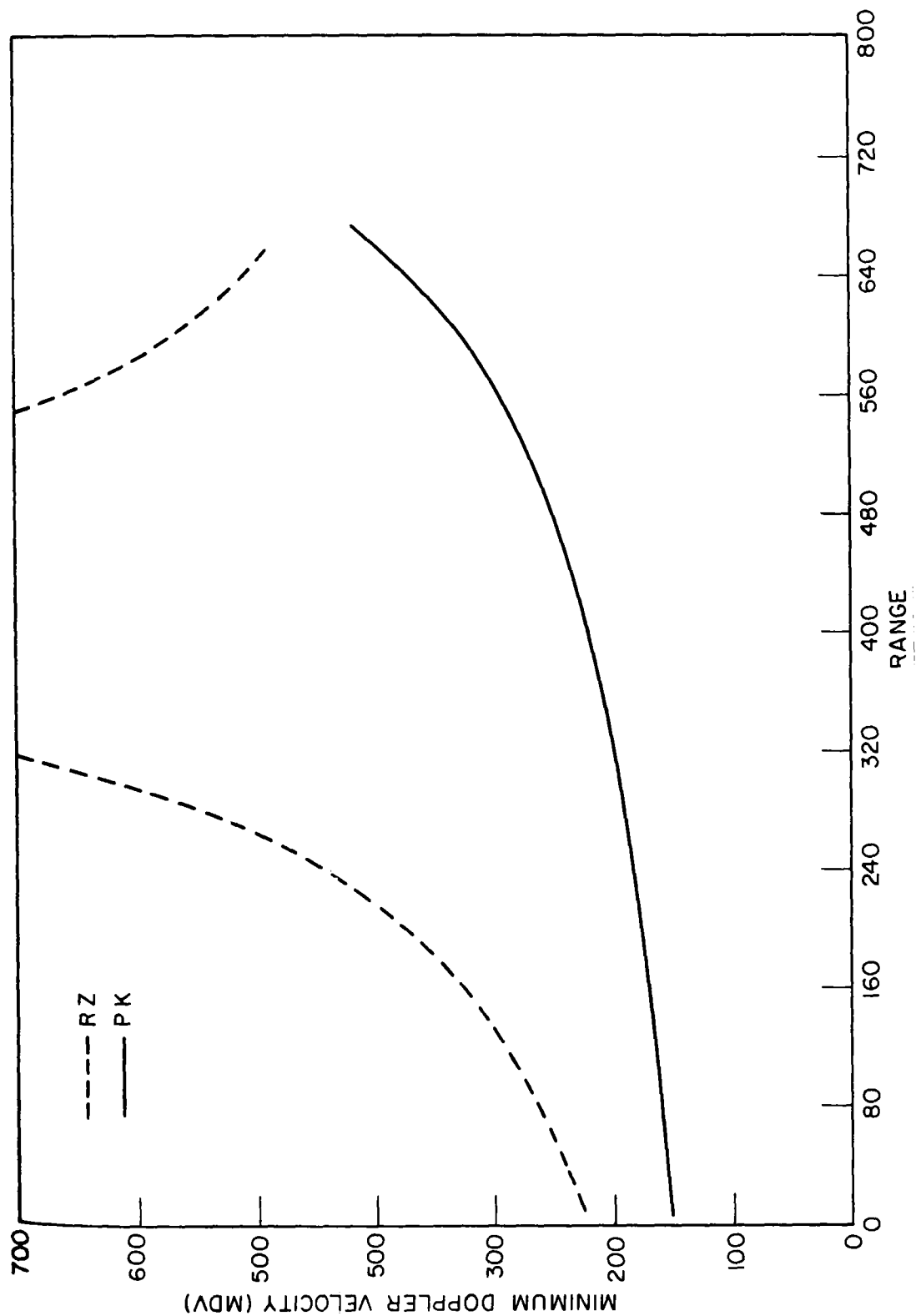


Figure 6. - Minimum doppler velocity, Moscow to Stryy

erecting antennas for all azimuths, with the freedom of powering the most likely  $60^\circ$  azimuth by selecting one which might produce the most data. From this site three  $60^\circ$  antennas can illuminate the Soviet Union on a  $180^\circ$  arc from 500 miles beyond Sary Shagan to Poland and Yugoslavia, except for the area immediately adjacent to the Black Sea.

Moving Target Population Counting Vs Tracking A versatile system for any chosen azimuth should be able to follow moving targets from take-off to landing or end of range and/or angle coverage of the equipment. This requires data from the radar on a particular moving target at time intervals of the order of three minutes or so. A Madre radar will provide range, radial speed and beam azimuth on every target detected in this period.

If one assumes, for example,  $5^\circ$  antenna beamwidth and 30 - 60 seconds dwell time in each beamwidth at 2 or 3 frequencies to cover the full range, then a  $60^\circ$  azimuth would be covered in six to twelve minutes. Assuming 200 aircraft in the air in the coverage area of the equipment at any one time, this gives a rate of 200 pieces of data which are available for handling each minute. The radar range is readily corrected to ground range; the indicated radial speed to true radial speed. If tracking is in mind it is preferred to predict each target's next point and then match received data against the prediction.

From the volume of data theoretically available the foregoing situation is too cumbersome for manual handling even though Madre can immediately separate, and display on separate channels, the approaching from receding targets. Some compromises suggest themselves here. In simplicity one man can count survey the displayed targets every 3 or 4 hours and record them for the range-azimuth sector in view. This allows considerable time for special areas of interest surveillance. In this manner the full potential is dormant, but if it becomes necessary to increase the rate to 10 to 20 seconds, this portion could be automated at a small increase in expense.

Considering the foregoing, this study will describe the simplest basic system to take a population count, concentrating interest on the selected  $60^\circ$  azimuth from eastern Turkey at ranges of 500 to 2000 miles. An increase in data rate is accomplished by upgrading the capability of such a site with additional transmitters and receiving equipment. Missile detection will also be held in mind and the necessary equipment proposed to detect them and possibly determine, for some, their radial velocity and acceleration.

Required Operating Frequency Range The frequency range required for an OTH radar can be calculated for any path, time of the day, month and period of the sunspot cycle by using Bureau of Standards data (Ref. 1 and 2). In this method, propagation by the F2 layer only is considered, which for the purposes of this report is deemed sufficient. In order to determine the extreme frequency limits in the chosen case it is necessary to consider only the limiting situations. The lowest frequency will be required during

a sunspot minimum, on summer nights while observing minimum ranges. The highest frequencies will be required during a sunspot maximum, on winter days while observing maximum ranges. With this as a background the following assumptions are made:

1. Twelve-month running average Zurich sunspot number - A minimum of 5 will be used since this is close to the mean of cycles 8 to 18. The mean maximum during this same period is nearly 100 and this figure will be used since higher values result in impractically high frequencies anyway.

2. Time and month - Summer nighttime conditions typically bottom out near 0300 local time in June. Winter daytime conditions prevail at 1300 local time in December.

3. Propagation path - The radar will be located at say  $40^{\circ}$ N latitude and  $40^{\circ}$ E longitude and will look generally due north. The ranges considered are 500 naut. mi. minimum and 2000 naut. mi. maximum.

The calculations resulting from the above assumptions indicates an operating frequency span of 5.7 to 36 Mc is required. These extreme frequencies will be effective 50% of the time under the assumed conditions. To increase the effectiveness to 90% would require a reduction of the above frequencies of 15%, or a 5 to 30 Mc coverage. In view of the extreme difficulty and cost of covering such a wide frequency span the following compromises are considered. Good results can be achieved in the range of 24 Mc when the maximum usable freq. (MUF) is 36 Mc; therefore, an upper design frequency of 30 Mc is believed feasible. Several difficulties arise in attempting to cover the low frequencies, the most important being antenna size, cost, and frequency span. It is possible to cover a 4 to 1 band with two antennas (Madre covers 2 to 1 with one antenna) and recent developments including Ref. 3 hold promise of covering the 4 to 1 band with one antenna. By using 30 Mc as the top frequency, a bottom frequency of 6 is projected, something close to the minimum requirement of 5 to 5.7 Mc which is indeed approximate anyway. This compromise is deemed good judgment because nothing is known of the ability of a Madre like radar to detect aircraft between 5 to 7 Mc. (Madre minimum frequency is 13.5 Mc) This states that the range 500 to say 750 miles is a gray area in range when these low frequencies are required.

Polarization and Antenna Form OTH radar will work effectively with either horizontal or vertical linear polarization. However, the choice may be determined by several facts presently in evidence. It is known for instance, from communications experience as well as the Madre system that even though transmission is initiated horizontally polarized, OTH returns contain both horizontal and vertical polarization. It is possible that right-left circularly polarized or a more costly diversity system could be devised using the experimental facts and this phase may be already under investigation by H.F. communicators, but the detailed designs are not at hand. The effect of short range (100 miles) reflections and of noise pick-up resulting from polarization choice is of little importance in a Madre

system since the first 100 miles or more are usually blanked out to remove local targets from display. The coverage pattern of the antenna is very little affected by the polarization and then only at low elevation angles which are useful at ranges beyond about 1800 miles. It would appear that vertical polarization would favor the 1800 - 2000 mile portion of the range. Economical construction and design problems could very well determine the chosen polarization since it is usually much easier to build a given antenna for its preferred polarization.

Antenna Considerations The Madre broadside array antenna has a gain relative to an isotropic radiator at the same place of:

| <u>db</u> | <u>at</u> | <u>freq</u> |
|-----------|-----------|-------------|
| 23.2      |           | 27 Mc       |
|           | and       |             |
| 19.4      | at        | 13.5 Mc     |

This antenna has consistently provided loop gain to allow OTH aircraft detection over the North Atlantic path when propagation conditions were Bureau of Standards (4) "poor to fair" or better. By comparison the Madre missile watching antenna has a gain relative to an isotrope at the same point of:

| <u>db</u> | <u>at</u> | <u>freq</u> |
|-----------|-----------|-------------|
| 15.1      |           | 27 Mc       |
|           | and       |             |
| 10.2      | at        | 13.5 Mc     |

It has been noted that this antenna has, at times, (propagation index 6) detected aircraft between 800 and 1800 naut. mi. while looking for missiles at AMR and PMR. The aircraft noted were present about 50% of the time.

It has been proposed that an antenna like the Madre broadside array be built with a 2 - 1 array on both sides, back-to-back, to cover a 4 - 1 band and the whole rotated for azimuth positioning. Lengths up to perhaps 350 feet might be considered feasible on this design, but when one contemplates a reasonable gain at say 7 Mc, dimensions become rather excessive.

Other designs suggest themselves as applicable to the problem at hand as shown by the BEMAWS study. The slot fed quasi half corner of RCA's is a vertically polarized antenna with wide frequency range possibilities. Here only the reflector is above ground, the only element to be stabilized above two mechanical cycles so as not to contribute to natural backscatter. The radial array of vertical log- periodic design proposed by Sperry, Ref. 3, has possibilities though both of these antennas must be provided with an adequate ground screen.

At the present time array type antennas have been limited to less than 2:1 frequency band because of element spacing. Wide band elements such as log-periodics or spirals have been designed with a frequency band as great as 10:1 with uniform patterns, gain and impedance match. Using these elements in a conventional array would result in a variation in effective element spacing from  $\lambda/2$  at the low frequency end to  $2\lambda$  at the high end of a 4:1 frequency band, causing intolerable grating lobes and very poor phase scanning characteristics at any frequency much more than about perhaps 80% above the low frequency end. It seems reasonable, however, to believe that an array can be developed with a combination of element sizes which will allow an effective element spacing of less than one wavelength over a frequency band of 4:1 or more if desired. For system simplicity it would be desirable to feed through the highest frequency elements into the lower frequency elements and on to the lowest frequency elements without the need for switching. Since in principle a single log periodic or spiral element does this already, it seems possible that a number of elements in series would behave properly in this way. Figures 7-12 show a variety of ways in which wide band elements could be assembled into a phase steerable array.

The preceding sketches do not exhaust the possibilities but considerable development work is needed on any proposed broadband antenna to optimize parameters for phase scanning over a 4:1 or 8:1 frequency band, since it has not been attempted to date. Arrays with circular symmetry have the advantage of uniform patterns over wide scan angles but in general the phasing techniques are considerably more difficult. The easiest way to phase a circular array is by use of a circular flat plate lens in a configuration as shown in Fig. 13. Such an array has a scan angle of  $\pm 45^\circ$  with excellent patterns. However, its frequency range is again limited to less than 2:1, so at least three would have to be stacked up to cover the desired band.

Such a system is perfectly focused, and scans half the angle from the array that the feed angle is displaced. In order to scan  $180^\circ$  two flat plate lenses would be needed, or electronic duplexing of feeds would be required. If power amplifiers were inserted between the lens and the array, and electronic gates were inserted at the lens feed and output points a suitable antenna for Madre would result. Figure 14 shows a side view of what such a structure might resemble.

The Madre broadside array antenna is 330' x 140' or 42,000 sq. feet. At 21 Mc the gain is 21 db. If this aperture were employed for 6 Mc the gain would be about 15 db, too low for reliable aircraft detection. Therefore, the probable solution lies in fixed position multiple antennas with beam steering to cover the desired azimuth. This also makes more orderly the expansion in azimuth at a site.

Beam Splitting It is understood that a desirable feature is azimuth knowledge to  $\pm 2^\circ$ , preferably  $1^\circ$ . This accuracy can be accomplished with a monopulse arrangement and this requirement should be kept in mind when the choice of antenna design is established.

Beam Steering Antenna phase changing for beam steering purposes is accomplished by two methods. The Madre system uses mechanically driven

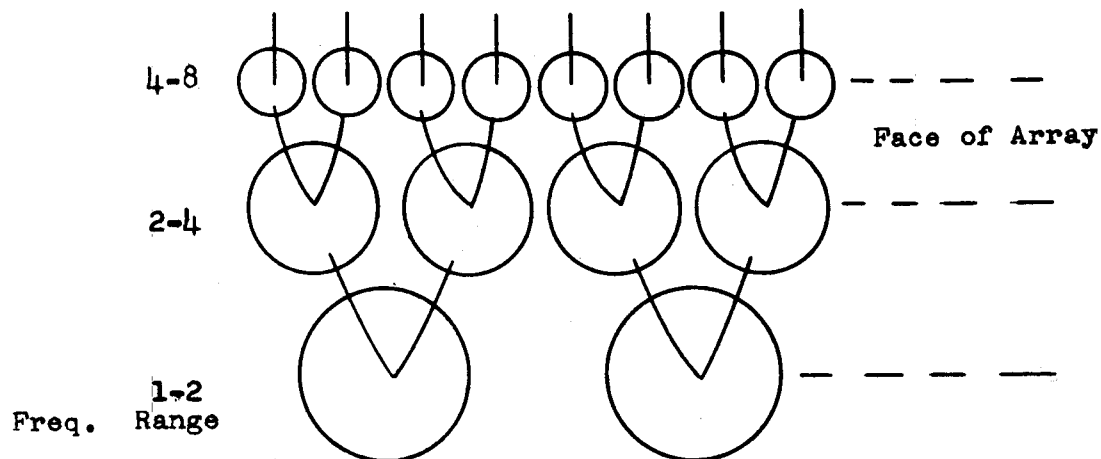


Fig. 7- Array of Spirals or Log Periodics

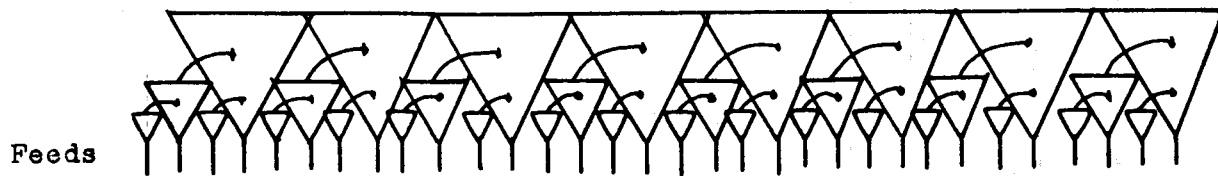


Fig. 8- Interlaced Array of Log Periodics (Top View)

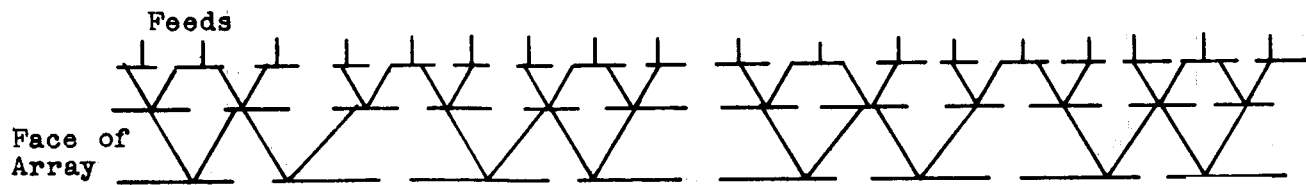


Fig. 9- Resonant Coupled Tapered Dipole Array

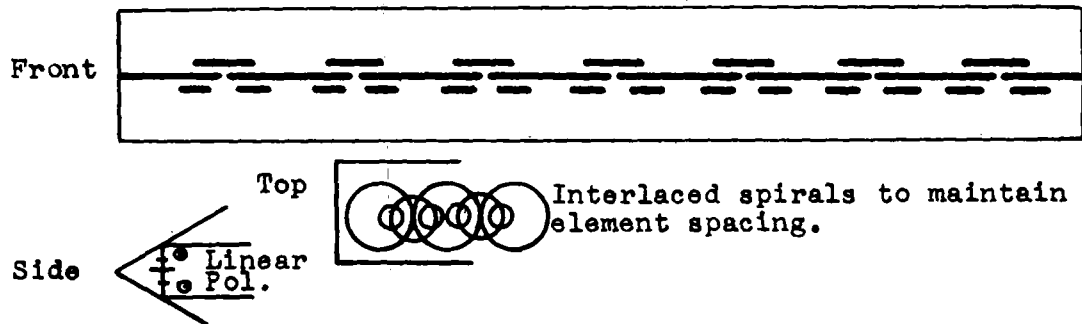


Fig. 10-Spiral Array in Corner Reflector

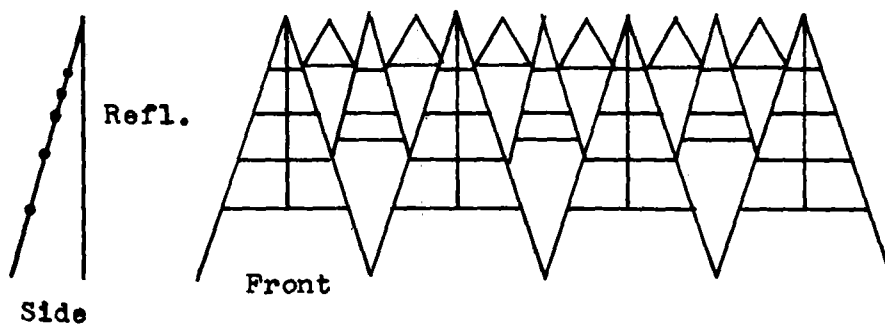


Fig. 11- Progressively Resonant Dipole Array with Broadside Beam

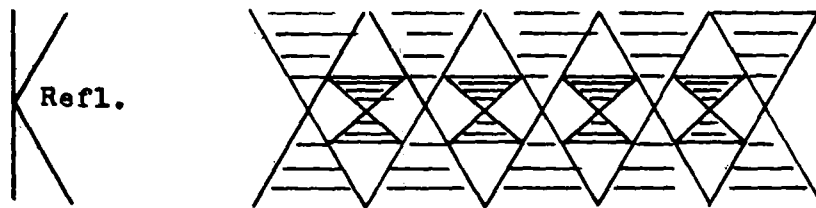


Fig. 12- Dual Dipole Array (double Fig. 6)

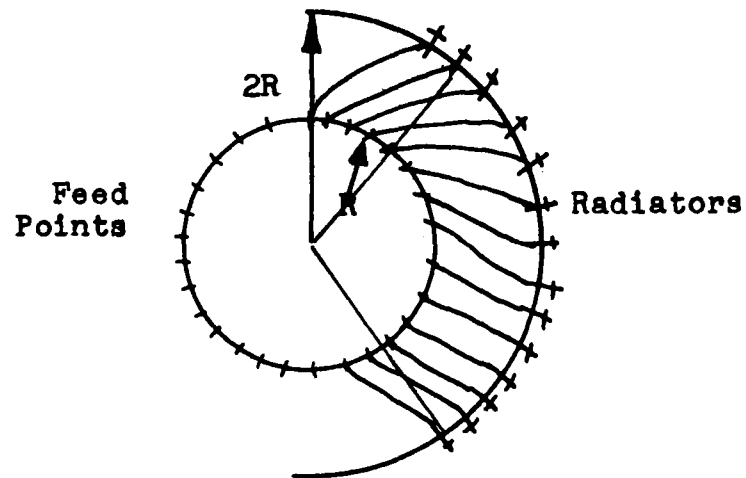


Fig. 13- R2R Lens Array

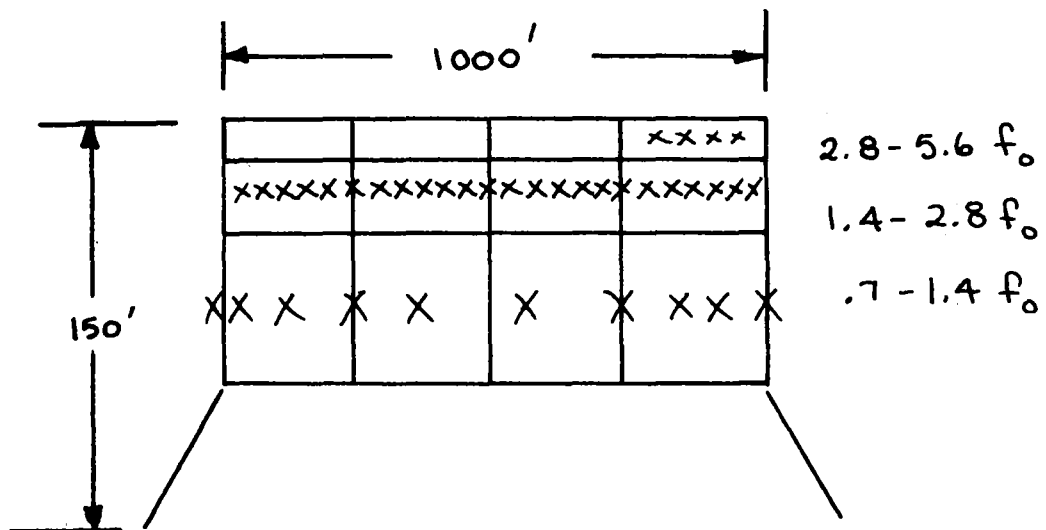


Fig. 14- Stacked R2R Arrays

variable transmission line lengths (trombones) to change phase. This method is slow and cumbersome but should be relatively trouble free and is not inconsistent with low data rates. A switching system, to move the beam in half beamwidth steps, is an attractive alternative to trombones. Mechanical means are most suitable when the antenna is driven from a single power amplifier.

The other method uses separate r.f. power sources to each antenna element so that the phase changing may be done at the low level inputs to the r.f. amplifiers. Such a system is complicated by the need for multiple r.f. amplifiers and duplexers, and received signal combiners. However, its feasibility has been demonstrated in several systems such as ESAR and it is capable of a high data rate. The distributed system is also capable of having different transmit and receive patterns. For instance, a broad beam could be transmitted and multiple sharp receiving beams used. However, the loss of gain on transmit would unduly degrade any OTH radar unless compensated by increased power output.

The 60° scan of the Madre broadside antenna design is felt to be an outside limit since a deterioration of pattern for a broadband antenna occurs at the maximum steer angles and in the worst case could be as high as a 5.7 db loss of one way gain. The side lobes are also up to -6 db at extreme steering angles. A possible compromise would be accepting less than 60° scan, but an even better compromise would be accepting slightly less than 2 to 1 frequency range in the active set of radiators.

Concentrated Vs Distributed R.F. Powering It is believed that the distributed system of R.F. powering is superior to the concentrated method for several reasons. A failure in the concentrated or single power source, puts the station off the air, whereas individual failures in the distributed system would potentially disable a single radiator or a bay from the antenna system. The required power levels and bandwidth of a radiator or bay of radiators is indeed reasonable in a distributed system; a concentrated power source for 600 KW average might present some development problems. The switching and phasing problems in a distributed system are electronic instead of mechanical. Presumably developments in electronic steering have progressed to the point where its reliability has been established. Distributed systems require a multiplicity of duplexers, preamplifiers and phasing matrices, but these are at a lower power level so that development is not introduced. The multiplicity of similar items is also advantageous from a repair and spare standpoint.

Problem of Transmission Medium Dependability The proposition under consideration is that of a very long range radar capable of aircraft detection and tracking. HF signals reflected from the ionosphere provide the means for attaining very long ranges. The case to be treated is that for great circle ground distances between 500 and 2000 naut. mi.; that is, a one reflection mode employing the F layer for reflection (the E layer may be useful for the shorter ranges at times). The near range limit is set by the lowest frequency capability of the radar and is somewhat arbitrary; the long range limit is imposed by the earth's horizon with respect to F layer altitudes.

(a) Ionospheric Reliability - As a first step in reliability estimation consider the general question as to available time for which the ionosphere is suitable for reflecting HF signals. Outages derive from (1) solar flare disturbances which cause excessive signal attenuation in the lower ionosphere and have durations of the orders of minutes to a few hours, and (2) ionospheric storms which cause both increased signal attenuation and degradation of ionospheric reflectivity that may last from several hours to several days. These factors affect HF transmission paths in a manner that is a function of latitude, and the reliability will vary from about 98% in equatorial regions to perhaps 60% in the auroral zones. Some rough predictions of timing for storms can be obtained but not for degree of severity, hence outage periods are not forecastable at the present state of knowledge.

The reliabilities stated above are probably attainable in a HF over-the-horizon radar at the expense of a very elaborate, flexible, and high powered system. Insufficient data have been collected to accurately state reliabilities and detection probabilities for any given HF ionospheric radar design and sufficient data will not exist for some time. It must be remembered that the ionosphere's cyclic behavior (daily, seasonal, 11-yearly and longer term) is known only on an average basis and carries a considerable random component. Therefore, a comparison with HF communication experience should furnish an estimate of radar potential.

Communications-Radar Comparison Consider the Madre radar with 100 KW average and 5 MW peak radiated power. The 20 db, over an isotrope, antenna has maximum gain of 26 db over the earth. Assuming a 6 db path loss, the power density at several distances has been computed and is tabulated below. The average aircraft echoing cross section as determined using the Madre radar on transatlantic flights is about 250 M<sup>2</sup>. In this 250 M<sup>2</sup> area two-way path losses have been absorbed; this conservative size has been used to compute the reflected power from aircraft due to radar illumination.

| Range<br>naut mi | Average<br>power density,<br>watts/M <sup>2</sup> | Average<br>reflected<br>power, watts | Peak power<br>density,<br>watts/M <sup>2</sup> | Peak<br>reflected<br>power, watts |
|------------------|---------------------------------------------------|--------------------------------------|------------------------------------------------|-----------------------------------|
| 500              | $0.9 \times 10^{-6}$                              | $2.3 \times 10^{-4}$                 | $4.7 \times 10^{-6}$                           | $1.1 \times 10^{-3}$              |
| 750              | $4.1 \times 10^{-7}$                              | $1.0 \times 10^{-4}$                 | $2.1 \times 10^{-6}$                           | $5.0 \times 10^{-3}$              |
| 1800             | $0.7 \times 10^{-7}$                              | $1.8 \times 10^{-5}$                 | $3.5 \times 10^{-6}$                           | $0.9 \times 10^{-3}$              |
| 2000             | $0.6 \times 10^{-7}$                              | $1.5 \times 10^{-5}$                 | $2.6 \times 10^{-6}$                           | $0.7 \times 10^{-3}$              |

There has been extensive experience in HF communications with aircraft employing conventional AM telephony. To affect a comparison the radar signal processing and receiving antenna advantages over the communications case need to be taken into account. The radar signal processing should give better than a 30 db advantage over AM telephony and the radar receiving antenna has about 10 db gain over the extensively used communication "billboard". Thus 40 db can be added to target reflected powers for a direct comparison with aircraft communications transmitted power, and this is tabulated below.

| Range<br>naut mi | Comparative<br>average power<br>reflected, watts | Comparative<br>peak power<br>reflected, watts |
|------------------|--------------------------------------------------|-----------------------------------------------|
| 500              | 2.0                                              | 110                                           |
| 750              | 1.0                                              | 50                                            |
| 1800             | 0.18                                             | 9                                             |
| 2000             | 0.15                                             | 7                                             |

These power levels are considered fair for comparison with voice communications transmitted from aircraft. According to L. Chertok, the Deputy Operations Officer, 2045 th Communications Group, Andrews Field, HF communications to Andrews from aircraft employing nominal 100-watt transmitters in the 500 to 2000 naut. mi. distance zone are quite reliable and estimated to be effective 90% of the time. The aircraft 100-watt AM voice transmitters would have at best 50 watts peak power and perhaps 5 watts average. In this treatment factors have not been biased to make the radar operation look possible; in the particular instances of target cross section and radar data processing advantage rather conservative figures have been used. Thus Madre radar performance should be roughly comparable to the communications example and the limited radar experience confirms this comparison.

Probability of Detection Estimates In order to be more specific in target detection reliability some of the radar system parameters will be selected. The lowest required frequency will be determined by conditions existing at a sunspot minimum and at 0300 June local time. The radar location will be set at 40°N 40°E and the look direction as north. Using CRPL data and methods the lower limit of F2 layer MUF's (Maximum usable frequencies) can be estimated as given in the following table.

Position 40°N 40°E, Bearing 0°, 0000Z, June, and RASSN (running average sunspot number) = 5

| Range, Naut. Mi. | Max. Usable Freq. | Max. Usable Freq. |
|------------------|-------------------|-------------------|
|                  | 50% of Time       | 90% of Time       |
| 500              | 5.7               | 4.9               |
| 600              | 6.2               | 5.3               |
| 700              | 7.0               | 5.9               |
| 800              | 7.8               | 6.6               |

For a number of reasons (antenna physical size being a major one) 6 Mc is selected as the lowest operating frequency. This selection causes detection reliability to be lowered in the 500 - 700 naut. mi. interval (that is, for two or three years out of each eleven and then only during summer nights). A high frequency limit will be selected that is five times that of the lowest giving 30 Mc (a principal reason being antenna design difficulties). During periods of sunspot maxima and in the daytime 30 Mc can fall far below the MUF for 2000 naut. mi. As a consequence of this condition and some other factors good operation out to 2000 naut. mi. will not always

be attainable. However, in the 1000 naut. mi. range interval between 800 and 1800 naut. mi. it is estimated that it is possible to illuminate adequately aircraft targets 80 or 90% of the time. This estimate is based upon: a 200 KW average power Madre-like radar located and with look angles as have been described above; frequency utilization of slightly below MUF for narrow range intervals (perhaps each 100 naut. mi. increment at shorter ranges); aircraft relative speeds in excess of 100 knots; and the availability of 4 KC bandwidth frequency channels essentially free of manmade interference. Some abridgment of these provisos seems desirable for a basic system. For the one-hop mode under study whereas the MUF determines the shortest possible range, the longest useful range at any frequency may be set by lower ionospheric layer shielding, D layer absorption, reflecting layer height, or a combination of these effects. Study of CRPL data suggests that simultaneous operation on three frequencies will provide fair continuous coverage of the 500 - 2000 naut. mi. interval. In any case, periodic backscatter soundings can show if adequate coverage is realized, if not - more frequencies than three (at the expense of a slower data rate) can be used to fill in coverage gaps. Figure 15 is intended to show a means for obtaining three frequency coverage. Frequencies 1, 2, and 3 must be selected to give the desired coverage with the aid of oblique backscatter soundings.

The conditions under which a probability of detection figure can be given should be reviewed. Actual HF ionospheric radar experience in detecting aircraft covers the past two years with the Madre experimental system. A limited number of frequencies between 13.5 and 27 Mc have been used. In addition to the restricted frequency range and short time of experience, many other features necessary for adequate testing of range coverage and reliability of the technique were absent in the experimental setup. Under these conditions an overall reliability of the ionosphere path 70 - 90% of the time seems reasonable.

False Targets Meteor ionization trails are the principal source of natural "false" targets. These trails have velocities up to 100 knots and can have a very large echoing cross section for a short time. Meteor trail echoes can be recognized by their short lifetime (seconds to a few minutes). They do impose a dynamic range requirement on the radar receiving and signal processing system - even greater than that required for handling backscatter. If a low data rate (low PRF) system is used where all aircraft target velocities are folded over and occupying the meteor trail velocity region, system performance would be quite inferior at times of high meteor activity.

Auroral ionization echoes are not likely to be confused with those of aircraft. However, aurora echoes appearing in a range interval of interest (perhaps via an antenna side lobe) can seriously reduce signal-to-noise ratio.

Missile Detection Missile detection, of secondary importance in this report, is covered in detail by Appendix A.

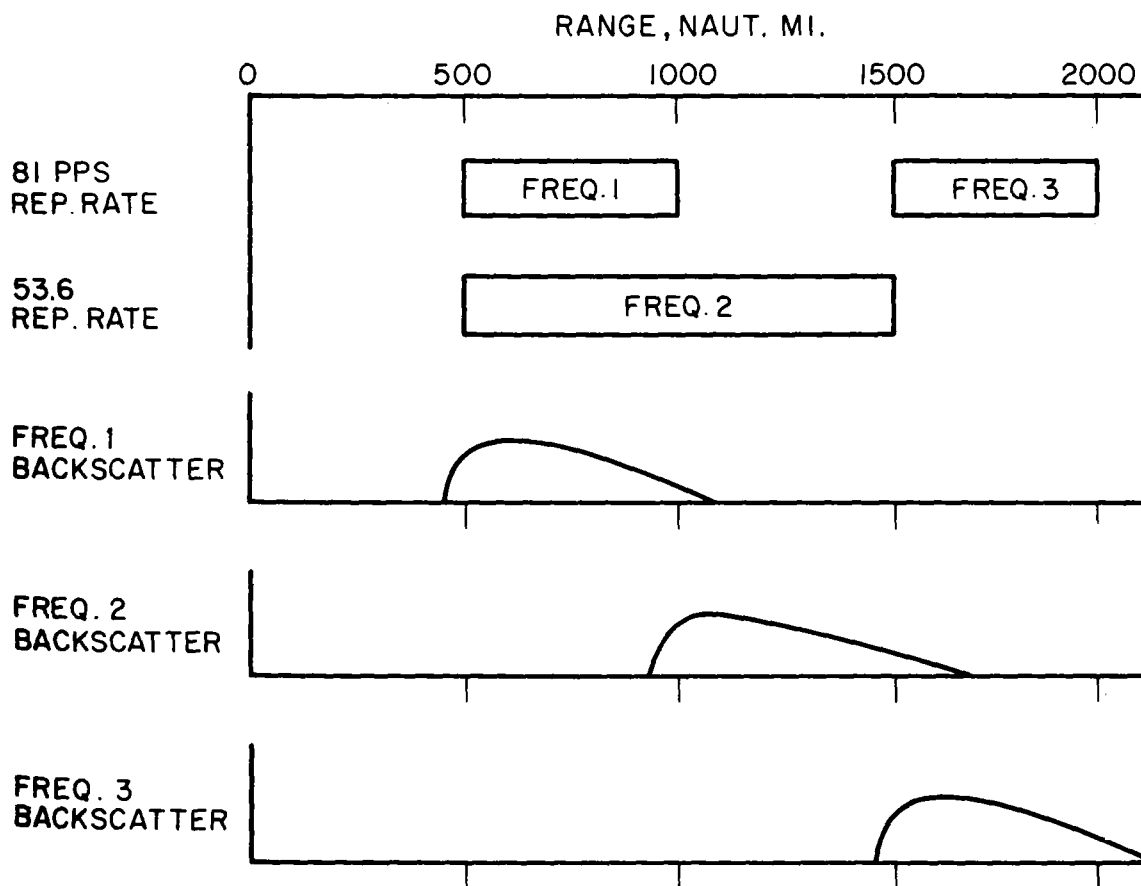


Figure 15 - Example of three frequency coverage of 500-2000 naut. mi.

## PROPOSED STATION ELEMENTS

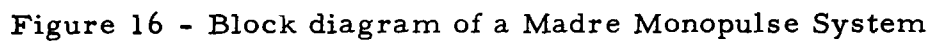
Station Location - Pin-Pointed Area A position in eastern Turkey has already been mentioned as a suitable situation. It is indeed advantageous to pin point the exact location in an area perhaps equally distant from the Black Sea, Adana and the nearest Syrian border. Such a position would minimize the chance of local jamming by Russian fishing boats in the Black Sea and eastern Mediterranean Sea and from other sources over the border of Syria. If one draws a 150-mile arc from Giresum on the Black Sea, another arc from the nearest Syrian border, northeast of Jerablus, and another from Dortyal on the Mediterranean coast, it will be found that the latter position is sufficiently far away to be ignored and that the first two describe an area of suitability. The eastern portion of this area substantially includes the towns of Arapkir, Cemisgezek, Pertek, or just north of Elazig. This general area is near Diyarbakir which already enjoys military support, communications facilities, and general supply means. The possibility of a shipborne installation is covered in Appendix B.

Topography and Electronic Isolation It would be good engineering for a Madre installation to be at least 35 miles from the electronic location near Diyarbakir. It is felt that Elazig, the nearest town mentioned, more than meets this important requirement. The topography of the immediate location could advantageously include positioning the radiating elements on the top of a hill or the north slope of a mountain where the land falls away to the northward in a 180° arc and the skyline to the northward on this arc does not materially hinder the launching of a 3° vertical main beam.

Comments on Military Support If a site is chosen in the recommended area, it is believed that the required military support, supply, guard force, data handling, data communications facilities, etc., can be supplied by an augmentation of the existing operation much better than the installation of a new and separate one. It is believed that the chosen site would best provide its own power frequency facility rather than augment the existing facility capacity and transport, at high voltage, the required load, over 75 miles or so of transmission line which must be maintained and guarded from sabotage.

Antenna Requirements The desired frequency band is 6 to 30 Mc. If this range is accomplished in a single unit such as RCA's slot-fed array, design compromise should be on the 6 to 7 Mc end for economical reasons. Successful Madre operation requires a rigid antenna system where natural mechanical vibrations contribute doppler components only below say 2 cycles, where the undesired doppler formed is handled by the comb filters. If mechanical design is known well enough, a non-rigid antenna system with the same minimum doppler characteristics would be satisfactory. The rigid design is preferable because the Madre results and experience are based upon its use. If one were to split the desired range into an upper and lower range, the individual antennas should be maximized at their center frequencies, otherwise that which is required is 20 db gain at about 14-Mc over an isotrope at the same position. The antenna must provide monopulse capability and beam steering  $\pm 30^\circ$ . The antenna elements must sustain operation at the power levels stipulated under transmitter requirements.

Transmitter Requirements The transmitter requirements are best understood with a general review of a distributed system with monopulse capability. Figure 16 is an example where an array covering 60° azimuth is envisioned to be made up of 32 antenna elements. It is noted that the left (1 - 16) and the right (17 - 32) halves are accompanied with the same number of duplexers, each one with a transmit and receive terminal.



Each duplexer transmit terminal is provided with a 20 KW average (310 KW peak) distributed class B amplifier with the banks of sixteen fed from a transmit (left and right) steering matrix. The power output was selected in the event that simultaneous transmission at three frequencies might be needed in the future for an augmented data rate. The driver for the steering matrices is also a distributed amplifier which accepts the shaped pulse from the programmer-frequency select system at the selected frequency. The latter frequency is the result of a look-through and transmit on an idle channel basis in a band centered on each of the nominal frequencies (generally 3) selected to cover the full range.

Each transmitter and its driver would be advantageously supplied by separate dc, plate, filament and bias sources with the plate supplies of the transmitters capable of smooth variation to full output. For economy, the number of plate power supplies may be diminished where a bay of transmitters could be fed by one larger supply. The power amplifiers must be gated off by grid pulsing during the listening period.

Receiving Requirements The receiving requirements are best understood by reference to Fig. 16 also. Here the receiver outputs from the duplexers (1 - 16) and (17 - 32) go to the left and right hand steering matrices. The output from these matrices are combined to provide a terminal "sum-receive" and another "difference-receive" for receiver processing and azimuth determination. An idea of the necessary receiving and pre-record equipment is set forth next with a consideration of "sum channel" processing.

Receiver - Pre-Record Equipment Azimuthal determination to  $\pm 2^\circ$  requires processing of both the sum and difference signal. What follows constitutes general receiving characteristics whatever channel is in mind.

HF receiver and pre-processing equipment for Madre-type operation have restrictions which preclude the use of some common radar receiver practices such as agc because their use would degrade performance. In some respects this tags the Madre receiver as old-fashioned, yet its design novelty will be apparent.

Figure 17 is a simplified block diagram of the electronic equipment to perform the titled mission. It consists of a multi-stage preamplifier at signal frequency followed by a local oscillator mixer which converts to 500 KC i.f. for further conversion. The desire for a constant output frequency and the convenience of designing clutter filters and approach-recede filters at 100 KC shows the output of the i.f. amplifier converted to a constant 100 KC frequency for filtering and input to synchronous detectors through approach-recede target separating filters.

Dynamic Range The design of the receiver must consider several basic factors. First the dynamic range must be large enough to permit linear amplification of extremely low-level signals (microvolts) which comprise the target return along with high-level signals (millivolts) due to (a) backscatter clutter returns from the large illuminated area and (b) those due to other users within the passband of the receiver.

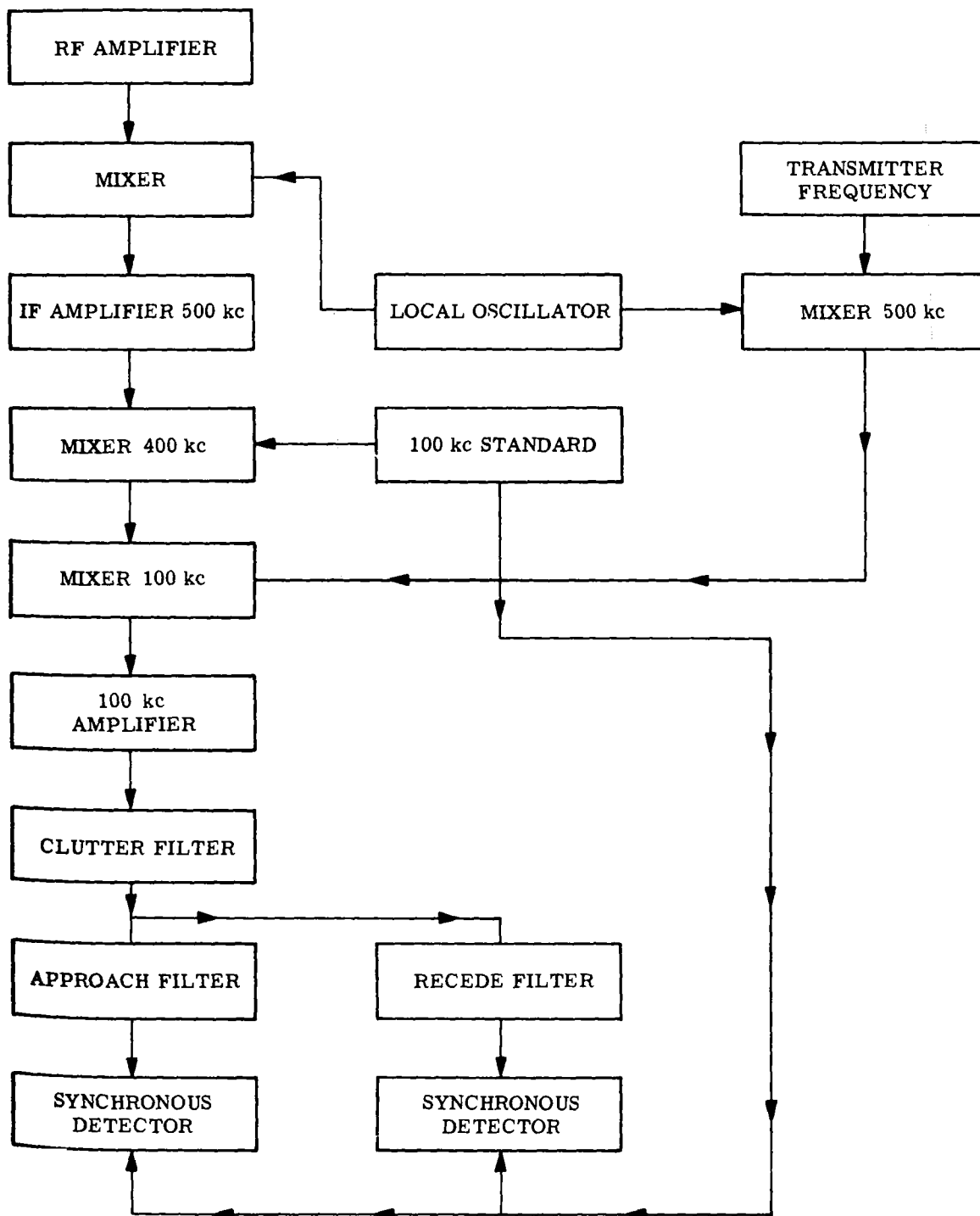


Figure 17 - Block diagram of Madre receiver

The required dynamic range is based on the effective reflecting area of the target compared to that of the illuminated area. A few very reasonable assumptions indicate that a dynamic range of 100 db or better is desirable. Operating experience with the receivers herein described indicates that the ratio of backscatter amplitude to signal amplitude often reaches 105 db.

Receiver Gain and Bandwidth The gain of the receiving system must be sufficient to amplify the low-level target returns to a level necessary for successful processing. This must be done with stable frequencies, stable gains, and without the introduction of additional modulation on the desired signals. The receiver must exhibit instantaneous recovery after overloading due to strong signals, including very strong meteor returns, and must, of course, have adequate selectivity and bandwidth to handle the desired signals properly while rejecting any undesired signals as much as the state of the art permits.

The gain of the receiver must be adjustable to suit existing conditions so in practice the gain is usually reduced considerably below the maximum available. Because of other considerations, the receiver output is delivered across a 100-ohm resistor and maximum output is about 10 volts rms but that desired is about 100 volts.

Receiver bandwidth for Madre purposes can be a minimum of 4 KC and the minimum is recommended. The actual bandwidth of the Madre receivers employed throughout the evaluation program is 16 KC. This design was used to provide some frequency stepping features as well as allow some leeway for some frequency drift.

A perfect receiver of 16 KC bandwidth would have a 50-ohm input noise voltage and would require a receiver gain of about 153 db. The receivers actually in use have a noise figure of about 9 db and gain of 140 db. In practice, the receivers are normally operated at much reduced gain due to conditions and at an output level of about 0.35 to 1 volt rms.

The total gain is divided about equally in the RF and IF stages with separate manually operated gain controls.

Frequency Range In compliance with Madre's antenna characteristics the receivers in use cover a frequency range 13.5 to 27 Mc. A second group of receivers has been built to cover 6.75 to 13.5 Mc in anticipation of a lower frequency change in Madre's capability. There is no problem in providing HF receivers for the 6 to 30 Mc band considered in this report.

Design and Shielding Extreme care was used in the receiver circuit and layout design to employ precision made, high quality parts to eliminate any regeneration or parasitic oscillations, since such effects produce nonlinear amplifications, spurious frequencies, undesired overloading, change in bandwidth with gain setting, unstable gains and tuning and, in general, exhibit undesirable results.

The receivers were constructed with adequate shielding between stages and filtering of necessary interstage connections so that there is no indication of regeneration or parasitic frequency generation. The shielding and filtering also reduce susceptibility to interference as it insures that only signals introduced to the receiving process are through the antenna terminals. An overshield is also used to enclose the complete receiver with the necessary filters in all power leads. This design is so effective that essentially no signal output from the receiver, tuned to the transmitter frequency, occurs where the input terminals of the receiver are capped and the transmitter operated at 100 KW power.

Gating and Blocking Duplexers are not perfect and some transmitted energy reaches the receiver when the transmitter pulse is on, but gating is effective in preventing receiver output due to the transmitter. The time and length of the gate pulse must be appropriate for no receiver output during transmitter on time. This gating circuitry must also not produce spurious display responses at the output of the system. Meteor returns are very often many times the amplitude of the backscatter. When the receiver gain is set for maximum usable gain under prevailing conditions, a meteor signal may produce severe overloading. All signal information is destroyed for this time interval but sensitivity is restored in a few microseconds following such overload.

Power Frequency Hum The receiver must not introduce additional frequencies on the output due to power supplies and filament heating. Well filtered and regulated plate supplies are required and well filtered dc supply for heaters is recommended.

Image Frequency Response The three-stage preselection employed in this NRL design provides adequate image response rejection of the order of 50 to 80 db.

Comb Filtering The high level, low doppler backscatter response must be eliminated for the desired signal to be amplified to a usable level for processing. Two methods have been employed for this purpose. Originally Madre used a cancellation delay line comb filter operating in the audio frequency range. Subsequently superior crystal comb filters were designed in accordance with NRL Report 5589 and sufficient teeth built in the model shop for several operating repetition rates. These rejection filters tuned to reject the carrier and backscatter side frequencies operate on a band of frequencies centered at 100 KC, where high Q crystals were available permitting rejection filter design with steep skirts. The comb filters employed are flat top with an 85 db theoretical rejection. In the presence of 60-cycle hum they checked out at better than 70 db. More rejection could be employed and can be obtained. It is believed that the addition of a deep notch at the carrier would improve the rejection of carrier and nearby backscatter components another 70 db. Use of these filters requires that the receiver IF frequency of nominal 500 KC, but subject to possibly several kilocycles variation, be converted to a band centered at precisely 100 KC. NRL comb filter design will take about 20 volts input. This could be increased to 100 volts without difficulty from crystal heating.

Frequency Converter This precise frequency conversion (Fig. 17) is accomplished by a separate unit into which the nominal 500 KC IF output is fed and conversion to a band centered at 100 KC occurs without perceptible deterioration of the signal. A reference frequency consisting of the difference frequency between the transmitted frequency and the local oscillator frequency is obtained by a sub-mixer. This reference frequency is approximately 500 KC but varies due to changes in both local oscillator and transmitter frequency. The reference frequency and a secondary standard 100 KC signal are mixed and the nominal difference frequency of 400 KC produced to mix with the nominal 500 KC receiver output to obtain the 100 KC accurately centered signals desired.

All the precautions which relate to the receiver must also be applied to this converter. In addition, extreme care must be used to insure that no output occurs due to the 100 KC from the frequency standard directly. Harmonic-free frequencies are obtained in the 500 KC to 100 KC frequency converter by use of adequate filters at all required interstage points and by operating both mixers at input and output levels so that grid current does not flow and plate current cut-off does not take place.

The frequency converter used in the Madre system does not produce any detectable spurious signals internally. Limiting circuits are built into the input stages for both 100 KC and 500 KC reference frequency so that changes in input level (above a certain minimum voltage) do not change the amplitude of these frequencies internally. A multiple section LC filter is used to filter the nominal 400 KC output from the 100 KC - 500 KC mixer so that frequencies of 100 KC and 500 KC are attenuated more than 80 db. Bias of mixer grids and internal reference signal amplitudes are adjusted to obtain optimum sensitivity without overdrive of the grid voltage.

Because of the possible range of input frequencies around 500 KC, the amplifiers for 400 KC and 500 KC are relatively broadband, about 24 KC. The 100-KC output stages are designed for a bandwidth of about 5.2 KC. Sensitivity is adjusted such that an input of less than 50 millivolts rms is required for an output level of 10 volts. The output level is normally about 20 volts peak-to-peak. Noise output of the converter unit in the absence of 500 KC signal is about 700 microvolts.

Approach-Recede Target Separation The separation of approaching and receding targets before subsequent data storage and handling is an enormous advantage for the practice of a moving target population count or a moving target tracking study.

The block diagram, Fig. 17, shows the comb-filtered 100 KC fed to the separate approach-recede filter banks with each one provided with a product detector output. NRL has already demonstrated the feasibility of approach-recede separation using magnetostriction filters. Crystal filters, to provide Madre with this capability, are readily obtainable. NRL's Supply Division is now handling the bids from a number of possible manufacturers to procure this hardware financed from USAF Madre support funding.

Synchronous Detector The outputs of the crystal comb filter fed approach-recede channels consist of the low-level desired signals, unrejected components of backscatter, plus all components produced by interfering signals. Neglecting the interfering signals, these 100-KC signals now consist of the spectrum of the return signals which differs from the original signal frequency spectrum because of the doppler effect. The amplitude of these desired signals at this point is in the order of 2 millivolts or less. These signals must now be converted to the audio frequency band by use of a product or synchronous detector. This unit is a form of balanced mixer circuit in which the comb filter output signals are mixed with the 100-KC secondary standard. The output of the mixer is passed through a suitable low-pass filter and the a-f spectrum of 0 to 2000 cps is thus available for further processing.

Considerations of linearity of amplification and hum-free operation are of great importance in the synchronous detector. Those presently in the Madre system have a total harmonic and noise output 60 db below the desired signal. Noise output in the absence of input signal is of the order of a few hundred microvolts. A synchronous detector is sensitive to both amplitude and frequency modulation and both forms of modulation by powerline frequency and its multiples are to be avoided.

Display and Data Extraction The proposed system requires a different technique for display and data extraction depending on whether its prime use is as a population counter or for tracking. The first method of display of data to be described will be as a population counter, the second will be as a generator of target tracks. In the second system the population counter display will be used as a monitor for system performance.

In the receiver complex the targets are separated approaching from receding. This means that there will be two range rate-range displays, one showing the approaching targets and the other the receding targets. These can be Madre displays of radial speed vs. range of the aircraft. In the simplest method of data extraction a man could count the number of targets he sees on each display on a cyclic basis and record the number. This method should have a backup of magnetic tape recording that would preserve the display information. This can be examined at leisure or be sent to the U.S. for more precise study. The manual approach could be augmented by a manually operated counter that prints out the number counted and the pertinent data such as date, time, antenna azimuth, and range block. It could be further automated by a threshold device which counts the number of targets above a given level. The next step in automation could be to record the range and speed of all targets detected. The above procedure should also employ a magnetic tape of the output for future study.

Moving target tracks could be generated with the above facility by manual means, however, if there are very many aircraft in the air at one time a swath of  $10^\circ$  azimuth, 500 miles long would soon saturate the operator or operators so that automatic track generation would have to be considered.

This can be a storage tube display with the added information on selected targets displayed. The storage tube would retain the information from the last sweep over an area and allow comparison with the next sweep.

Drum Storage System The Madre system requires a multiple channel signal processor. This can be similar to the analogue storage drum used in the NRL research system which has 33 db dynamic range. An alternative design which offers better than 60 db dynamic range has the steps analogue to digital conversion, storage of information in digital form and then a digital to analogue converter. This type's promise of increased dynamic range will provide additional CCM capability and much reduced target masking by meteors, etc. Also variable repetition rates and integration times are by-products of this approach having a very considerable advantage. Also it will aid the operators as it will not require the precise receiver gain adjustments now necessary with the 33 db dynamic range of the Madre research system. This digital system has not been reduced to hardware, but NRL scientists and at least two prospective contractors believe it can be accomplished. NRL has initiated a study phase with both RCA and G.E. for this feature. NRL believes that it can be furnished in time to be incorporated into the first installation of any proposed operational system, and therefore NRL recommends its inclusion.

Madre CCM Features It must be recognized that the Madre signal level at one hop ionospheric ranges is likely to be the strongest in the band because of its high power. For this reason early detection and analysis of the transmitted signals are to be expected. Since Madre must operate with reflected signal levels of the order of milliwatts, which with doppler processing are brought up to the equivalent of fractions of a watt, a jamming level of the order of watts is all that is needed to jam the main beam of the radar, and a few hundred watts can jam through the side lobes. For this reason, as well as from propagation considerations, Madre must be designed with frequency flexibility and quick reaction time to avoid both manually operated jamming efforts and normally occurring interference. It should not be assumed that the USSR will accept the loss of the information this radar would gather if electronic countermeasures are economically practical. Appendix C covers the vulnerability aspects in greater detail. For these reasons the proposed system is recommended to be provided with the following features which are considered available in the time scale.

There is considerable flexibility in the proposed HF system with regard to frequency range (2+ octaves), selected nominal frequencies (three) within the latter range to cover the desired radar range, and several megacycles latitude at the nominal frequencies about which it is proposed to operate on a look through for open channel and transmit basis. The maximum time on any one frequency is planned as thirty seconds (a good look) but this time can be cut to three seconds or so, if required, without great harm. It is stressed that any useful portion of the HF spectrum, at any one time, is enormously occupied and Madre has lived with interference jamming to some degree at all times. In the normal mode Madre does not call for a high proportion of a megacycle's channels to maintain sensitivity, for if one percent of the channels are open on a random basis Madre can

extract at full information capacity in the idle channel. It is not uncommon to experience 80 to 90% occupancy. This planning is conservatively consistent with DOD document S-27389/Q-2, page 3,1(a).

The RF preselection portion of the receiver will be equipped with minimum bandwidth to prevent degradation of the receiver's dynamic range due to other's useful signals-interference jamming.

The site has been selected to minimize ground wave propagation jamming at close range from boats in the Black and eastern Mediterranean Seas and from over the border in Syria.

The Madre proposal calls for better than 60 db dynamic range with the memory processing. NRL feels that this can be achieved. This feature is a CCM facility which also provides minimum display overload and target masking due to meteoric returns and some undesired disturbances.

The comb filtering is conservatively rated at about 83 db rejection. This is about all one can expect in a single chassis treatment, but an additional set of combs could be added to double this capability. As an interim measure, this proposal calls for an additional 70 db notch at the carrier and repetition rate side frequencies to alleviate overloading of subsequent processing by strong signals.

Madre development work is now progressing on ARPA funding to investigate the generation of multiple sideband pairs to be applied to the range ambiguity problem. Here the carrier is suppressed and corresponding pairs are relegated to each desired range interval. The carrier for each range interval is reconstituted by addition of the proper sideband pairs. This system requires say sixteen KC or so RF bandwidth at the front end of the receiver for a three-step practice and should work quite well in a moderately occupied spectrum.

The approach-recede target separation offers additional means to combat interference. If one were to display the approach information, except when coincident with recede information, there is a possibility of removing the display of modulation from any carrier locked on the Madre carrier. If such a carrier and modulator is displaced from Madre's center frequency, the side frequencies do not always provide the cancel state. This feature should be considered as an adjunct toward obtaining a clean screen. Coincident targets would also cancel but only for the period of coincidence.

High-quality well-regulated dc plate and filament supplies are recommended for both the receiving and transmitting equipment so that a doppler line at all ranges caused by a power line frequency or a folded harmonic thereof will not provide a secondary zero doppler base about which positive and negative doppler can be spread to overlay a portion of the desired primary doppler display.

The receiver output can be made to handle ten times or more the voltage it now is designed for (10V), if the processing methods described above are used. This would increase the dynamic range 20 db or more.

The foregoing indicates that the plan calls for the removal of secondary circuitry overloading characteristics and a receiver design with as much primary dynamic range as the state of the art permits.

Madre's Operational Potential The Madre system proposed for erection in eastern Turkey differs from the Madre research radar at NRL's Chesapeake Bay Annex in that it has been provided with the known factors of operational potential which are believed achievable within the period of an eighteen to twenty four month contract. These factors include wide frequency range, increased operating frequency flexibility and instantaneous scan of antenna beam, greater dynamic range in the receiver, comb filters and signal storage means; approach recede target separation; variable repetition rate; and a variable integration and frequency dwell time.

Ultimate Madre Potential The minimum "look time" (frequency dwell time) for integrating Madre is about three seconds. When and if the Russian capacity along with their desire to deny information produces an HF jamming network for OTH radars, with such agility, flexibility and effectiveness so as to deny a three second look, then it is stressed that the proposed Madre system has reached its limit of effectiveness and its operation may be impaired. In the event that there are generated no new means to prolong Madre's effectiveness during the period of foreign use, then Madre's operation must be augmented by additional channels or other means.

Expansion, Growth, and Research and Development Appendix D covers the future expansion and growth in site radar capability.

#### FINANCIAL FORECAST

It is preferable to cost the full implementation of the Turkish site and then show some compromises which can be made to spread the cost over a period on an expansion basis. Full implementation would require the installation of three 60° azimuth radars each with full signal handling capacity and separate operating ability.

Basic Radar A basic 60° azimuth coverage radar with monopulse and around-the-clock operating capability would cost, site installed in the USA, about ten million dollars. This figure includes cost and installation of 60-cycle power plant, radar civilian personnel housing and commissary requirements and power wiring. The cost of commercial documenting is included. Military documentation (10 - 30% of total cost) is not needed where operation and maintenance are purchased.

The basic 60° radar would require 16 men, e.g. (RCA Service Corp. or General Electric Field Service personnel) to man and service the equipment on a 24-hour basis so as to provide acceptable output, but these personnel would not handle or interpret the output data. The sixteen personnel would cost 0.5 millions/year and their required maintenance parts and spares another 0.5 millions/year.

Foreign - Based Radar If the basic radar were installed, checked out and made ready for operation in eastern Turkey, the following projection is made:

- 1 - 60° azimuth Madre radar @ 10M x (1.3 - 1.5) = 13 - 15M and  
3 - (three) at this figure are (13 - 15M) x (2.6) = 33.8 - 39M

Basic Radar Cost Breakdown The transmitters, antennas and signal processing equipment can each be roughly divided to account for about one-third of the total cost, though the antenna, depending on choice, may be half the total cost. The antenna is an important item which should not be compromised.

Compromise Installation Thus if one were to foreign install three 60° antennas at the eastern Turkey site to cover 180° azimuth and plan to share their use with transmitting equipment for just one station, the following costing is made:

- 3 - 60° azimuth antennas @ (4.6 - 7M) x 2.6 = 10 - 18.2M  
1 - transmitting, receiving complex with  
    housing and power facilities from  
    substation on @ 5M(1.3 - 1.5)                      = 6.5 - 7.5M  
Switching and transmission line @ 0.5M              = 0.5 - 0.5M  
Total Foreign Installed Cost                      = 17.0 - 26.2M

Cost Exclusions The radar site costs presented as best estimates do not include:

- (a) Maintenance, fuel storage and personnel requirements for the 60-cycle power plant and its distribution network.
- (b) Cost, maintenance and personnel for the needed microwave data and telephonic link between the chosen site and the established electronic area.
- (c) Cost and maintenance of fencing the chosen area and the guarding of same.
- (d) Land purchase or rentals.
- (e) Cost and maintenance of necessary roads.
- (f) Machine shop facility.
- (g) Tools for an electronic shop facility.
- (h) Military housing and housing for civilian personnel not connected with the operation and maintenance of the radar proper.
- (i) Commissary requirements for personnel under (b) above.

(j) Personnel (military or civilian) to study, correlate and prepare the radar output data in form for transmittal.

(k) Military documentation. Commercial documentation is adequate for hired operation and maintenance. Military documentation would increase overall cost 10 to 30% needlessly.

Time Scale The time scale is 18 to 24 months with a target of 21 months after signing contract.

## APPENDIX A

### MISSILE SURVEILLANCE

General A MADRE-like radar, that is, an HF coherent MTI radar employing backscatter clutter rejection and narrow band spectrum analysis of signals, has a great deal to offer in missile launch and re-entry observations. The frequency panorama or spectrum analysis as a function of range presentation of target features is an informative and sensitive technique. There are several different missile effects notable and a brief will be given:

1. For missile altitudes from the ground up to about 60 or 70 KM the radar requires enough power for skin tracking. Exhaust and shock ionization may enhance echoing cross section and add some doppler spreading but not by orders of magnitude. The missile track must be illuminated for detection.

2. The charge gradient created by the rocket exhaust moving up through the atmosphere from 70 KM to 300 KM affords a large echoing cross section (thousands to millions of square meters) possessing a diffuse doppler. The doppler components may spread over 100 cps, however, there is generally a pronounced intensification near the missile velocity doppler especially in the E region. This target is large and difficult to mistake; it has excellent features in that it exhibits the location and motion of the missile. Missiles with thrust termination in the E layer are detectable. The missile track must be illuminated; however, because of the large echoing area, direct, one hop, one and one-half, and two hop modes are practical.

3. When a burning rocket is illuminated by F layer waves that are experiencing refraction distinctive responses in the earth's backscatter can be noted. The effect is as though an additional moving and turbulent path or paths has been created. Signals via these paths have diffuse dopplers from 30 to 90 cps in extent and can have an approach or recede sense or both, depending upon ray geometry with respect to missile altitude. The effects are prompt in that they commence while the rocket is in the F region, and they degenerate into a few cycles per second rumble on the backscatter spectrum after rocket exit from the F region. The burning rocket path must be illuminated in F region for detection of prompt effects; the low frequency rumble is propagated horizontally and may be detectable in propagation paths several hundred kilometers distant from the missile path.

4. Missile re-entry bodies can be skin tracked but are of small area and would require very high power. The re-entry ionization phase furnishes a larger cross section target with distinctive character. Good illumination of the track is a prime requisite.

In rocket and rocket effect observations it is very helpful to operate with a wide doppler availability. Range gated doppler versus elapsed time read outs have been found very effective. There are real possibilities of rocket trajectory parameter determination at long range. However, a relatively slow searching radar in range and azimuth could not be expected to have much use for missile surveillance. Relatively constant observation of missile launch regions is required for effective data. This is especially so for the detection of the AICBM (treated in the following paragraphs) for which the whole observable event may be no longer than 60 to 80 seconds.

AICBM Detection by HF Radar It will be assumed that a USSR AICBM will be a three stage rocket similar to the NIKE-ZEUS in size and general characteristics. At HF the radar cross section at various flight phases of the missile will be primarily determined by the maximum linear dimension in the plane of polarization of the incident wave and will be maximum when this dimension corresponds to a half wavelength of the illuminating frequency. The cross section of a parasitic dipole at resonance is about  $.86\lambda^2$ . This value is easily arrived at by considering the basic capture area of a dipole ( $A = \frac{G\lambda^2}{4\pi}$ ), the increase in induced current by a factor of two due to the lack of termination in a parasitic dipole, and the gain of a resonant dipole of 1.63 over an isotope

$$\sigma = AG = \frac{G^2 \lambda^2}{4\pi} \left(\frac{i}{i_0}\right)^2 = \frac{G^2 \lambda^2}{\pi} = \frac{(1.63)^2 \lambda^2}{\pi} = .86\lambda^2 \quad (1)$$

$\sigma$  = radar cross section

A = effective capture area

G = dipole gain = 1.63

$\lambda$  = wavelength

$\frac{i}{i_0}$  = ratio of current in a shorted termination to the current in a matched termination = 2.

Figure 1 shows typical dimensions of an AICBM (NIKE-ZEUS).

Table 1 shows the resonant frequencies of the various rocket stages, values of radar cross section at these frequencies, and an estimated value at fixed frequencies of 10 and 20 Mc, as well as the estimated time of flight, velocity range, and radial velocity range of each stage.

| <u>Max. dimension</u> |     | <u>Resonant frequency</u> | <u><math>\sigma_{res}</math></u> | <u><math>\sigma_{10}</math></u> | <u><math>\sigma_{20}</math></u> | <u>V</u>          | <u>V<sub>r</sub></u> | <u>h</u>       | <u>t</u>     |
|-----------------------|-----|---------------------------|----------------------------------|---------------------------------|---------------------------------|-------------------|----------------------|----------------|--------------|
| 1st stage             | 45' | 11 Mc                     | 660                              | 500                             | 400                             | 0<br>1500 mph     | 0<br>150             | 0<br>10 K      | 0<br>5 sec   |
| 2nd stage             | 27' | 18 Mc                     | 238                              | 25                              | 200                             | 6000 mph          | 600                  | 10 K<br>100 K  | 5<br>22 sec  |
| 3rd stage             | 14' | 35 Mc                     | 63.5                             | .4                              | 6.3                             | 6000<br>6000± mph | 600±                 | 100 K<br>500 K | 22<br>80 sec |
| 1st & 2nd span        | 14' | 35 Mc                     | 63.5                             | .4                              | 6.3                             |                   |                      |                |              |
| 3rd span              | 7'  | 70 Mc                     | 16                               | .11                             | .007                            |                   |                      |                |              |

Table 1

From Table 1 it is obvious that the first and second stages have radar cross sections and radial velocities of the same order of magnitude as aircraft targets and therefore should be detectable with MADRE assuming the proper scan. The third stage, however, is quite small and requires a system capability of detecting a target of only a few square meters peak radar cross section. This implies a subclutter visibility about 20 db better than is required to detect a typical aircraft of 200 square meters at HF frequencies. However, this is a possible target that might be detected under good conditions because of its altitude, and in addition the acceleration program of the AICBM should allow separation of its signature from typical ICBM's, SRBM's, and satellite launches, even if the last stage cannot usually be detected. It is quite possible that frequencies can often be chosen such that ground clutter at the rocket range is small or nonexistent even though the field strength at 100,000 to 500,000 feet is enough to see the small third stage.

Figure 2 shows a possible AICBM flight envelope.

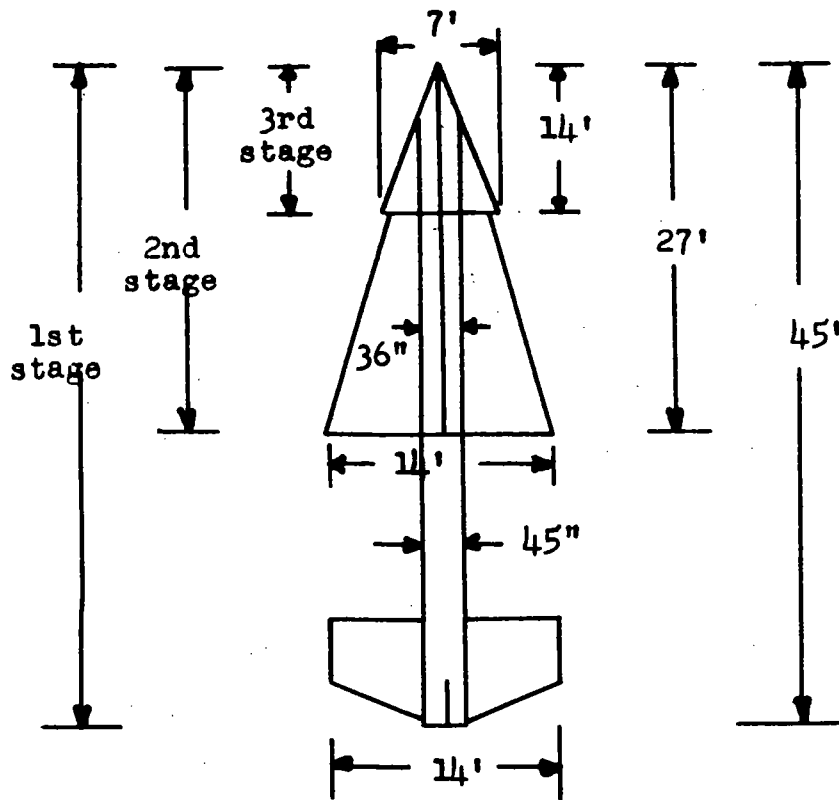


Fig. 1

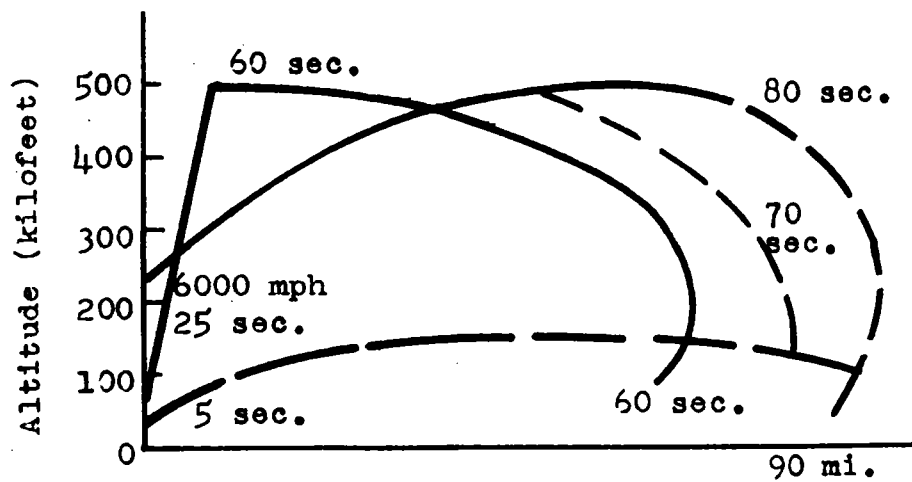


Fig. 2

## APPENDIX B

### SHIPBORNE VERSION OF MADRE

The planning of the operational application of an HF radar involves many decisions, running from the selection of the parameters of the radar (or basic radar element) itself, through choices of suitable installation sites to considerations of the political and ECM environment which should be anticipated. Some of these decisions can be based on reasonably firm and complete scientific knowledge both theoretical and experimental, while others, including some of a technical nature, are handicapped by incomplete or not fully applicable information. The political climate is obviously one of the most difficult to foresee and choices in this regard, if they can be made without too great a cost, should allow as much flexibility, or adaptability, of the installation as possible.

Since a complete surveillance system is expensive, even if some rather important compromises in coverage capability are accepted, it is quite possible that as the initial step only a single basic radar element may be procured. If this is the case the choice of site may be rather difficult. It will, for example, involve loss of aircraft traffic counts in lanes near a tangential geometry and there will be the question of sacrificing missile detection capability to obtain the greatest coverage against aircraft, since the activities may be geographically widely separated. A 60-degree sector seems about as great as other requirements on the system will permit in the basic radar element and the antenna size dictated by the sensitivity and subclutter capability required for aircraft surveillance would make it extremely expensive if not impractical to use a rotatable antenna whose 60-degree sector of coverage could be positioned in various directions.

These technical factors along with political considerations make it reasonable to consider some other type of installation -- a type of platform with mobility. This obviously might be a ship. Ships are being used very successfully to carry large and complex radar and electronics installations. The MARS and DAMP ships as well as the KINGSPORT are examples. Not only are the receiving, transmitting, data processing and operating facilities taking up a large part of the space on these ships but large multiple antenna systems on the topside are characteristic of the installations. Satisfactory measurements, using sensitive and highly accurate equipment, are being made from these ships.

However, the MADRE antenna compared to the antennas in these installations presents quite another situation. The MADRE at CBA has an antenna 330 ft. x 140 ft. and weighs about 400 tons not counting 550 tons of concrete ballast at the 100 foot level. It's minimum operating

frequency is limited to 13.5 Mc. An operational system for around-the-clock surveillance must have a capability of a much lower operating frequency and the minimum acceptable horizontal dimension probably is about 450 feet. The vertical dimension of the antenna should be at least 100 feet. It is seen that this structure, although much more open than parabolic antennas or UHF arrays, would dominate the topside profile of any ship. It's length would be  $2/3$  to  $3/4$  that of a good sized ship.

An artist's depiction of the possible appearance of such a shipborne antenna is shown in Figures 1 and 2.

The particular antenna configurations shown in these sketches are only representative. Various design suggestions are under consideration. Log-periodic or flat spiral type radiators are desirable since these are elements having wide bandwidth characteristics -- approaching 10 to 1. As shown in the preceding text, the broad band antenna is a prerequisite to a satisfactory operational HF radar system. The primary difference between the design for shipboard use would be the shipboard limitation on size to approximately 500 by 100 feet -- and because of this accepting a minimum frequency of operation of about 8 Mc rather than the 6 Mc, as well as lower gain, proposed for a larger ground system. Even though an 8 Mc minimum is significantly above the 6 Mc desired minimum, the shipboard system should still have an important capability in this respect -- the additional cost is in lost operating time primarily in the early morning hours -- midnight to sunrise, particularly during the poorer sunspot years.

In the CBA MADRE system, special attention in the design was given to reduction both in the amplitude and frequency of movements of the antenna caused by wind. Structurally independent towers form the array, each of which is loaded with 50 tons of concrete ballast at the 100 foot level. Such a measure as heavy ballasting is obviously impractical for shipboard use. However, it is believed that shipborne operation is feasible except possibly during a particularly high sea state, for the following reasons:

1. Use of a shorter integration time with a corresponding reduction in velocity resolution will relax the movement limitation proportionately.

2. If sailing, slow speeds should keep vibration to a minimum and roll and pitch of the ship, while high in amplitude, are at rates well within the bands rejected as an anti-clutter measure. Dual antennas, back to back, shown in the figures would permit reasonable on-station sailing patterns.

3. If at anchor, vibration, roll and pitch amplitudes should be still lower than when under way.

A more penetrating analysis of the shipborne installation of an operational MADRE is not believed justified at this time. The primary purpose of this section is to draw attention to this possibility and the advantage of a mobile site should only a single basic radar element be built.

The advantages and disadvantages a shipborne system would have relative to a fixed site are listed below:

#### Advantages

1. Reduced, even negligible, obligation to the site country. Ship might operate in open seas or at anchor in or near a friendly port.
2. Installation of radar, fitting out of ship, and check out of system in home port with evaluation of coverage over friendly known land areas.
3. From a given operational area (site) shift of the 60-degree coverage to any desired direction, merely by changing ship heading. One 60-degree sector might be observed for a period then another, etc., for any desired sequence or observation time.
4. Shift site for radical changes in area covered for such purposes as changing the orientation of lost tangential flight patterns from a previously observed coverage area to one allowing these flights to be observed, changing from coverage of European USSR to an area even as remote as Kamchatka, or, for example, to allow test observations of our own aircraft or missile events.
5. Shift of site to provide best coverage of an area in which some schedule of events is expected although this area might normally not be an interesting one to cover.
6. Learn, without involving other friendly countries, the reaction of the USSR to this type of observation both from the ECM and political viewpoints.
7. Obtain valuable technical information useful for better choice of ground sites and the effect of geographical location, climate, etc.
8. Obtain technical information of value in the improvement of the design of later HF operational radars.

# ESCORT AIRCRAFT CARRIER

CVE (105-123) "BLOCK ISLAND"

DISPLACEMENT: 12,000 TONS

DIMENSIONS: 553 (OVERALL) X 75 X 30½ (MAX. DRAUGHT)

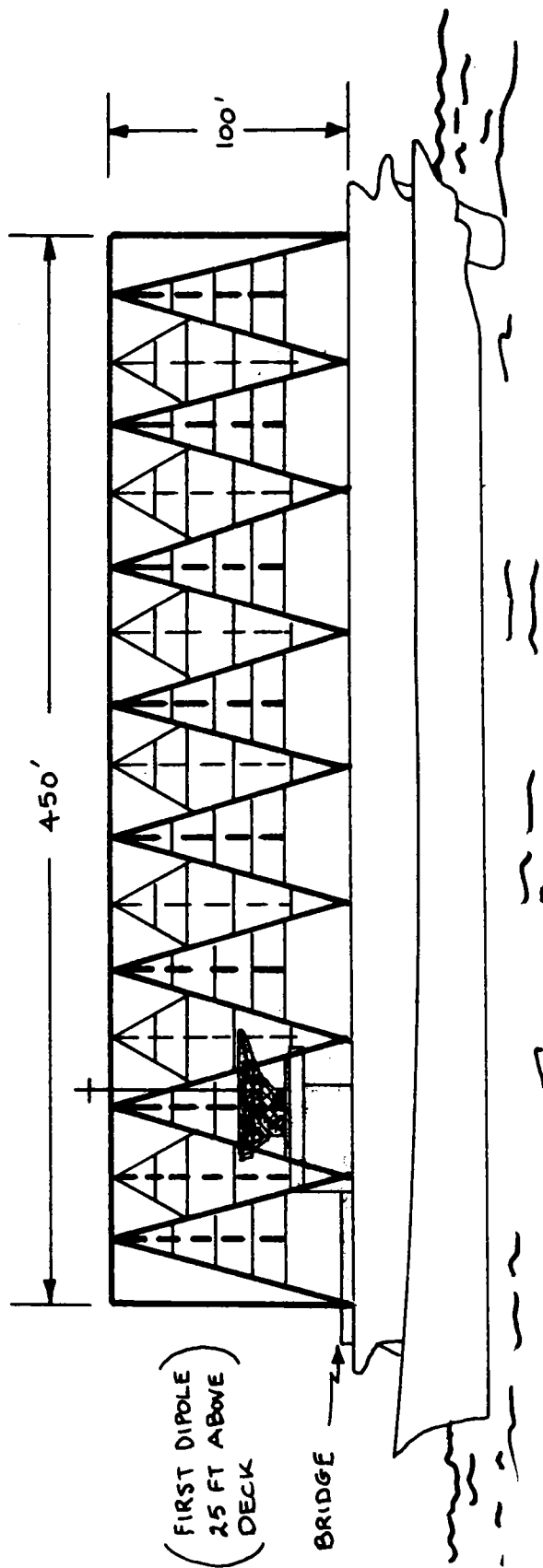
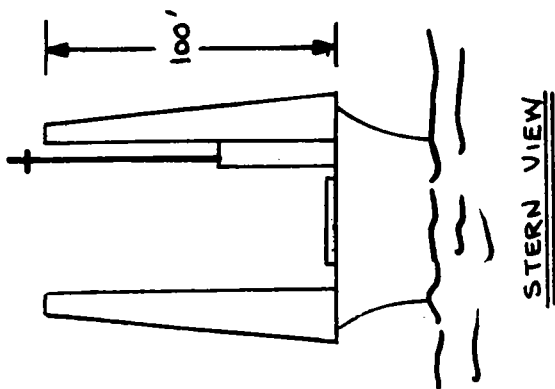


Figure 1 - Shinborne Version, Side and Stern View

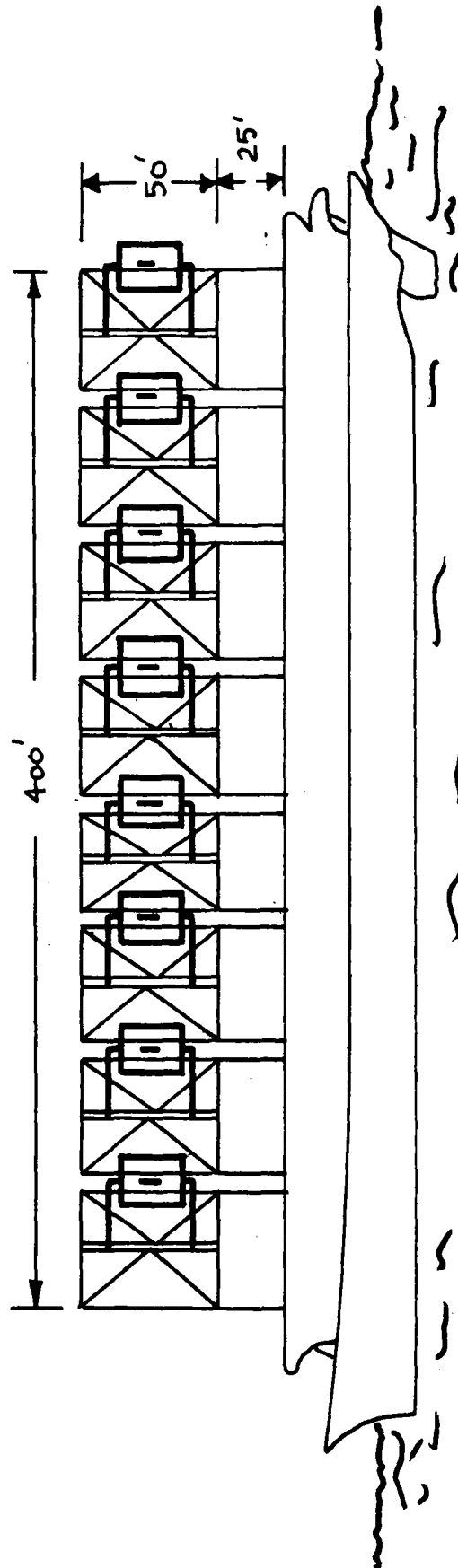
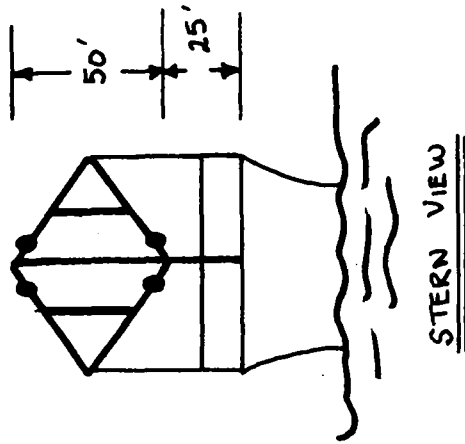


Figure 2 - Shipborne Version, Side and Stern View

9. Should land sites later be equipped with operational MADRE, the shipboard installation may continue to be used as part of the overall complex.

#### Disadvantages

1. Owing to limitation on antenna size reduced performance will result over what might be achieved on a ground based site, including a higher minimum frequency of about 8 Mc, rather than 6. This would lengthen the outage period when ionospheric conditions are unfavorable.

2. The minimum distance of approach to USSR boundaries will, in some situations (from the Arabian Sea for example), cost up to 200 miles in range coverage. From many operating sea areas, however, the stand-off of up to 500 miles is not a disadvantage and can be made less if need be.

3. Cost of such a facility should be comparable to a similar land site only if a suitable vessel is available at nominal reconditioning cost. The use of a ship such as a CVE or CVL would, as seen in the sketch, require complete removal of the island structure and provision of a bridge, probably forward of the antenna.

4. Maintenance costs. The KINGSPORT carries a crew of 50 ship's personnel and 30 electronics people. The latter are for maintenance and operation of the elaborate electronics equipment on board. A larger CVE or CVL with MADRE probably would require twice as many in the first if not in both categories. A ship's company of this size can, of course, provide only minor maintenance of the vessel and periodic availability periods for this purpose would be required.

## APPENDIX C

### ECM VULNERABILITY

- Summary 1. An HF radar operating for a significant period of time (more than a second or two) on a single frequency or narrow band of frequencies is extremely vulnerable to electronic jamming and spoofing. Jamming power levels of a few watts at target ranges (1000 to 2000 naut mi) are adequate to disable the main beam of the radar, and power levels of a few hundred watts are adequate to jam through the side lobes.
2. Of necessity the peak power level of MADRE at target ranges is 30 db or more above that of a typical 50 kw HF broadcasting station with 10 db antenna gain. This means that a threshold device with a frequency counter and time interval counter can measure frequency and pulse length and be able to direct a manual jamming system on frequency with a delay time dictated by the reaction time of the operator. An automatic jammer or repeater could be initiated by the threshold detector -- a technique well in hand by our own countermeasures people.
3. Any of a large class of spread spectrum techniques will theoretically allow operation of a radar over a wide band of frequencies without loss of coherence or efficiency except for dispersion in the medium. This reduces the power density per unit transmitted bandwidth and increases both the difficulty of reception and decoding as well as the total jamming power required. The state of the art allows compression of bandwidth (or pulse length) by a ratio as high as 1000:1. This would reduce the detectability of the signal by this factor and in the HF band where 50% band occupancy is typical, would require analysis of perhaps as many as 1000 frequency channels simultaneously of which 500 might contain extraneous interfering signals of similar amplitudes. Random coding would make the analysis in real time extremely difficult.
4. The ionosphere is a variable medium. Proper choice of frequency is vital in maintaining a low loss path to a particular region. Instantaneous knowledge of ionospheric conditions is extremely useful in the avoidance of multipath effects and other undesirable anomalies which cause dispersion and make single targets look like multiple targets. This is best accomplished by means of oblique sounding over the useful part of the HF band. With this information available frequency bands can usually be found where wide band non-dispersive transmission is feasible.
5. The use of wide band transmissions in the HF region must cope with considerable interference from occupied channels. This problem requires automatic spectrum analysis in the radar to inhibit operation at occupied frequencies.

- Recommendations
1. The MADRE system should be designed so that the antenna and transmitter are instantaneously wide band.
  2. Electronic scanning or array phasing should be incorporated to allow inertialess scan or simultaneous operation at all beam positions.
  3. The MADRE system should contain variable integration time and instantaneous frequency selection to avoid simple minded jamming.
  4. Nothing should be designed into MADRE which eliminates the possibility of using more sophisticated coding if the jamming situation should become intolerable.
  5. A filter bank spectrum analysis system should be incorporated into MADRE to provide information needed to avoid interference from occupied channels.
  6. Provisions should be incorporated in MADRE to allow a number of simultaneous independent channels within the 7000 or so microseconds of radar dead time between 0 and 600 naut mi. This will allow "simultaneous" operation of the system as an oblique sounder, multiple channel MADRE, and other type of pulse coded radar as experience dictates the need and added programing equipment is developed. In addition it will allow growth potential in increased data rate so that target tracks may be maintained.

Introduction When consideration is given to setting up a large and expensive system of radars for gaining information from within another country's domain, the possibility that there will be attempts to deny this information must be included. Information on aircraft traffic flow in the USSR is difficult to obtain because it is carefully protected. It would seem unrealistic to assume that such information is there for the taking if one resorts to the use of a radar system located outside USSR boundary. We must assume that if we are willing to invest several million dollars to gain this information the USSR will be willing to invest easily 1/10 that, if not an equal amount, to prevent our doing so.

All radars are susceptible to electronic countermeasures (ECM). The likelihood of the enemy's use of ECM may be gauged by the following factors:

1. The cost of an effective ECM system or complex of systems.
2. The disruption which the required jamming system causes in his own information channels (communications, radar, etc.).
3. The value which the enemy ascribes to the information being sought by an adversary's radar system.
4. The value of the information given by the jammer itself either as a pre-attack warning or as a beacon.

From the vulnerability standpoint the proposed primary use of MADRE -- for surveillance against aircraft within the USSR -- is one of the most difficult of the various tasks such a system might be called on to do. Aircraft targets are among the smallest which a MADRE might be used to detect and generally countermeasure action will not suffer the constraint of item 4 above.

The following Appendix of this paper gives full discussion of the ECM/ECCM situation for an HF radar system. Although in the inflexible manner in which the research type MADRE has had to be operated at the Chesapeake Bay Annex, it is vulnerable to ECM, a pulse to pulse frequency agility reduces this greatly, but more important allows the capability to provide a still less vulnerable system ultimately, if not at the time of installation. Only a system with this frequency shifting capability and ECCM growth potential should be considered for operational use.

A MADRE type HF radar will illuminate an area of the surface of the earth at one hop ionospheric ranges of something like 400 miles in depth and 100 to 200 miles in width at a mean range generally between 1000 and 2000 naut mi when operating at a particular frequency. If the frequency is stepped over a considerable portion of the HF band it will sometimes,

but not always, be possible to cover the total range depth. For closer ranges lower frequencies are needed, noise levels are increasing rapidly, band occupancy is higher, sporadic E layer propagation is more prevalent, and absorption is generally higher. The reliability of a useable radar range in the region of 600 to 900 miles is probably considerably less than for the longer ranges typical of F layer propagation. In order to make use of all propagation modes in an attempt to get maximum range coverage a total frequency coverage from about 5 to 40 Mc is desirable. There is no experience available from the MADRE program on the use of frequencies below 13 Mc. Tepee experiments at least as low as 8 Mc show considerable difficulty with sporadic E in the summertime, and many meteor echoes out at ionospheric propagation ranges. It is quite rare for the ionosphere to refract frequencies above 30 Mc back to the surface of the earth. Occasionally during periods of maximum sunspot activity frequencies as high as 40 or 50 Mc are refracted. The advantage of having a frequency range great enough to exceed the critical frequency is that it gives the radar the capability of line of sight tracking at long ranges on missile and satellite launchings which come within line of sight shortly after penetrating the ionosphere at ranges of the order of 1000 to 1500 miles. This will allow much improved tracking of such targets.

The vulnerability of the MADRE radar to electronic countermeasures will be determined by the ease with which the enemy can detect and classify the received signal, and by how fast he can react and come up on the radar frequency with sufficient jamming power. If MADRE illuminates 80,000 square miles at one frequency and beam position then at least one jamming station per 80,000 square miles of protected area is required in order to jam in the main beam of the radar. However, as shown later, the jammer power requirements are sufficiently low that side lobe jamming is feasible. If one MADRE site must cover an angular sector of 160 degrees (equal to an arc length of 4000 miles at 1500 miles range) and if it is vulnerable to jamming in the side lobes, then about 4 jamming stations in western USSR could jam the entire coverage. If the enemy so desires he can introduce false targets by repeater techniques and simulate a variety of traffic conditions, depending on his subtlety. Later calculations will show that the MADRE signal strength in some areas of the USSR will very likely be 10 to 30 db higher than any other signal in the band for any reasonable receiver site more than 50 miles from a high power local transmitter. On this basis one can expect that MADRE frequencies can be detected and analyzed with threshold devices, allowing either fast reacting manually operated jamming or automatic jamming or repeating devices.

If the MADRE system is located within line of sight of enemy territory (such as an enemy mountain) or within sight of possible aircraft over enemy territory the jamming power and number of stations required will

be reduced. For this reason it is probably preferable to locate the site over 200 miles from enemy territory and below line of sight of any enemy terrain.

It appears that the present experimental MADRE system with its requirement of sitting in one narrow frequency band for its integration period of 3 to 20 seconds is conceivably vulnerable to a manual jamming system. A modest jamming effort will deny information and a more subtle effort can provide realistic false targets which can simulate any desired air traffic situation, or can cover true traffic movements with a multitude of added targets.

There is really no complete answer to the ECM problem; the ultimate approach is to change frequency over the maximum useful frequency band as rapidly as possible, preferably pulse to pulse or better yet within the pulse to reduce the power density radiated in a given channel and to require the jammer to spread his energy over a wider bandwidth. In this way the jammer might decide to desist because in the process of jamming the radar he might also jam his own communication links severely. In order to reduce the vulnerability to repeater jamming one must use intrapulse spread spectrum coding techniques which change from pulse to pulse over a wide frequency band in order to make coherent repeating of a single pulse possible only at ranges greater than the repeater range. For ranges much greater, as required to introduce numbers of false targets in range, the wide band coherent delay required of the repeater is technically much more difficult, and the repeater logic is susceptible to interference and confusion by all signals which might appear in this wide band, in addition to the radar signal.

The simple conclusion is that the enemy can jam or can confuse if he so desires. A more sophisticated "instantaneous" wide band system can increase the difficulty of jamming proportional to the added complexity. It is recommended that any MADRE system developed for surveillance over the USSR be so designed that an instantaneous wide bandwidth is available in the expensive components such as transmitters and antennas, with the capability of electronic scanning or beam positioning so that more sophisticated programing and processing can be added if the need arises.

Radar Signal Detectability Equation (1) gives the signal strength at one-hop ionospheric distances.

$$P_r = \frac{P_T G_T F_A}{4\pi R^2} \quad (1)$$

$P_r$  = received power

$P_T$  = transmitted power

$G_T$  = transmitter antenna gain in direction of receiver

$F$  = propagation power gain or loss over free space due to ionospheric focusing, absorption, and ray path interference effects

$A$  = effective receiver antenna capture area =  $\frac{G\lambda^2}{4\pi}$

$R$  = range.

Substituting typical MADRE parameters into Equation (1)

$$\begin{aligned} P_r &= \frac{5 \times 10^6 \times 100 \times F \times A}{4\pi R^2} = \frac{5 \times 10^8}{4\pi} \cdot \frac{FA}{R^2} \\ &= 4 \cdot 10^7 \frac{FA}{R^2} \end{aligned}$$

Let  $R = 1000$  naut mi =  $6 \times 10^6$  feet

$G = 1.6$  = gain of a dipole

$\lambda = 15$  meters = 50 feet

$A = \frac{1.6 \times 2500}{4\pi} \approx 300$  square feet

$F = .1$  to 10, use value of 1.

$$P_r = \frac{4 \cdot 10^7 \cdot 300}{36 \cdot 10^{12}} \approx 3.3 \times 10^{-4} \text{ watts peak in the receiving dipole.}$$

If a 50 ohm impedance level at the receiver is assumed the signal voltage from the antenna will be  $\sqrt{RP}$  or  $\sqrt{50 \cdot 3.3 \cdot 10^{-4}} \approx .1$  volt. In other words MADRE will lay down a field strength of .1 volt out of a 50 ohm impedance transmission line connected to a dipole at a range of 1000 miles at 20 Mc. This can be modified up or down by about 3 to 1 due to variables in propagation gain or loss, giving a range of voltage levels of .03 to .3 volts.

In contrast to the signal level received from MADRE the level received from a typical 50 kw broadcast transmitter with an antenna gain of 10 db will be lower at the same distance by a factor of 30 db, or 30:1 in voltage (1000:1 in power). The range of the 50 kw signal for equal power to MADRE at 1000 miles is about 33 miles.

The MADRE signal level in unity gain side lobes is 20 db less which is still higher by 10 db than that of the 50 kw signal at equal range and is equal for a range difference of about 3:1 or 1000 miles versus 330. However, the 100 to 600 mile range is in the dead zone of the HF transmissions so the main concern of the intercept receiver is to locate himself sufficiently remotely from any local high power transmitters that ground wave transmission will not cause excessive signal levels. In this manner he can assure himself that whenever MADRE is capable of detecting targets anywhere in his zone (perhaps 400 miles in depth by a thousand or more miles in width) it will have a peak signal level probably 10 to 30 db stronger than any other signal in the HF band. The intercept receiver and signal analyzer now becomes a simple threshold device and is capable of analyzing within a pulse length for frequency and pulse duration with elementary digital analyzers such as a digital frequency meter and time interval counter. For a radar integration time of the order of 10 seconds it would seem that a manual operator could look through for about one second every few seconds in order to maintain his jamming on frequency, without losing jamming effectiveness. If the radar integration time is reduced to one or two seconds after which the frequency is moved to a randomly chosen new frequency the manual jamming effort would probably become fairly ineffective in following. The radar would pay a penalty in velocity resolution and signal-to-noise ratio for each look with shorter integration times, but it would increase the number of looks in unit time which with appropriate track memory would tend to compensate. For example, with 10 second integration time, 32 beamwidths of scan and 3 frequencies per beam position the total scan time would be about 1000 seconds or 17 minutes, and scan to scan target correlations would be lost (the target of interest having moved perhaps 170 miles in this time). With an integration time of one second the total scan time would be 1.7 minutes or 17 miles of movement, and scan to scan correlation, allowing target track generation would appear feasible. Present manually operated VOA jammers might follow any frequency shifts with a long integration time, but an automatic system would have to be used for following short integration times (3 seconds and less).

An automatic jammer system can easily detect and classify the MADRE signal in a short time because of its high signal level and narrow bandwidth. However, in order to jam the radar it must automatically select the proper frequency in the jamming transmitter and start transmitting with minimum delay, with appropriate look-through intervals to maintain jamming effectiveness.

Once the automatic jammer is considered a threat (which is well within the state of the art) the problem of a false target generator is well in hand, and may be easier than the brute force jammer, since look-through is not a serious problem. Microwave repeaters are already installed on some of our own ships. The repeater need only receive the MADRE pulse and repeat back a number of delayed pulses to simulate a number of targets displaced in range. Since MADRE operates on a fixed frequency during one integration interval the repeater need only reply on a fixed frequency anywhere within the 3 kc bandwidth of the MADRE pulse to simulate a velocity which is a function of the displacement of its frequency from one of the pulse repetition frequency side bands of the MADRE spectrum. If each repeated pulse is programed in frequency and delay multiple target tracks will be generated in the MADRE system which can simulate any desired traffic pattern.

If the MADRE becomes more sophisticated and transmits a wide band of frequencies within each pulse the energy level per unit bandwidth is reduced proportional to the spectrum increase. The digital frequency meter will now measure only an average frequency and cannot analyze the spectral distribution of the pulse. The jammer will then require a filter bank device to measure the disposition of the signal frequencies. However, since the signal energy per unit bandwidth has been drastically reduced the MADRE signal will now not be the strongest signal in the band and the filter bank analyzer cannot work on a simple threshold criterion but must use some other logic inherent in the signal to decide to jam. If the frequency coding of the transmitted MADRE signal is complex, and changed fairly often a repeater jammer becomes very difficult and brute force jamming requires a broad band which will jam a lot of channels MADRE is not using, creating a real nuisance to the USSR. For example, if MADRE transmitted a 1 Mc frequency band the energy per kc would be reduced by 1000 to 1. If the band were 50% occupied by other signals the analyzer would need to separate the MADRE signature from a conglomeration of perhaps 50 to 100 other signals, many of which were stronger than MADRE. This requires a very fine analysis and complex equipment to do in real time over even a 1 Mc band, and would need to be done over the total part of the HF band MADRE is using to be effective. Randomizing the signature pulse to pulse, randomizing the pulse rate and randomizing the frequency interval used is about the ultimate that the radar can do. These techniques are within the state of the art, as exemplified by the Typhon SPG-59 radar.

The process of spreading the frequencies in the pulse does not destroy coherence or doppler capability because the pulse is reassembled in a matched filter which coherently reassembles the signal into a compressed pulse with a phase corresponding to the average frequency with no energy lost. The effective pulse length is narrower but the effective peak power is increased by the process, and the jamming power required is also increased by this same factor.

The major conclusion of this section is that the simple MADRE wave-form will be easily detected and can be jammed effectively with a manually operated system if integration times are not reduced to the minimum required for target detection. If the enemy desires to develop automatic jamming or deception devices, the MADRE pulse must be coded as deceptively as possible to make the job more difficult for the jammer.

Minimum Self-Screening Jamming Range of a Target The simplest jamming case is that where the target is carrying its own jammer and desires to mask itself at ranges into some minimum distance from the radar. This is equivalent to a case where the jammer is located at a fixed site in the region to be masked which falls in the main beam of the radar.

Let  $P_T$  = radar peak power output,  $G_T$  = radar antenna gain,  $\sigma$  = target cross section,  $R$  = range,  $P_J$  = average jammer power over the radar transmitted spectrum bandwidth,  $G_J$  = jammer antenna gain,  $I$  = number of radar pulses integrated coherently (or the integration power gain in case of non-ideal integration),  $P_r$  = peak echo level at radar receiver,  $P_{r,j}$  = jammer power at radar receiver,  $F$  = propagation factor (power) one way,  $A$  = antenna area =  $\frac{G_T \lambda^2}{4\pi}$

$$1. \quad P_r = \frac{P_T G_T^2 \lambda^2 \sigma F^2}{(4\pi)^3 R^4} = \text{power at radar receiver terminals}$$

$$2. \quad P_{r,j} = \frac{P_J G_J A F}{4\pi R^2} = \frac{P_J G_J G_T \lambda^2 F}{(4\pi)^2 R^2}$$

3. Required jamming level =  $P_r IK$ , where  $\frac{1}{K} = \frac{S}{N}$  output required for desired probability of detection and false alarm rate  $\approx 20$  for most radar cases.

$$4. \quad \frac{P_T G_T^2 \lambda^2 \sigma F^2 IK}{(4\pi)^3 R^4} = \frac{P_J G_J G_T \lambda^2 F}{(4\pi)^2 R^2}$$

which reduces to

$$P_J G_J = \frac{P_T G_T \sigma F IK}{4\pi R^2}$$

For ionospheric propagation let  $F$  vary from .1 to 10 to take into account ray focusing and absorption variables,  $K = .05$

$$P_J G_J \geq \frac{.005 \text{ to } .5 P_T G_T \sigma F I}{4\pi R^2}$$

For a typical MADRE case  $P_T = 5 \times 10^6$ ,  $G_T = 100$ ,  $\sigma = 1000$ ,  $F = 2$ ,  $I = 1000$ ,  
 $R = 3 \times 10^6$  meters

$$P_J G_J = \frac{.01 \times 5 \times 10^6 \times 10^2 \times 10^3 \times 2 \times 10^3}{4\pi \cdot 9 \cdot 10^{12}}$$

$$= \frac{.01 \times 10^{13}}{3.6\pi \cdot 10^{12}} \approx 1 \text{ watt average noise over a 4 kc bandwidth}$$

If the jammer antenna is a log periodic element  $G_J = 8$  db or 6.3 in power and  $P_J = .16$  watts.

If MADRE uses 4 frequency side bands the total bandwidth is increased by 4 to 1 but the power per side band is one-half so the jamming power needs to be .32 watts.

If MADRE increases its power by 5 times, the jammer power needs to be increased by 5 times, leading to a 1.6 watts requirement.

At the present status of MADRE data the factor  $F$  is hidden in the target cross section data. Measured cross sections vary from perhaps 10 to 10,000 square meters. The median value is about 200 square meters. Very likely the distribution is Rayleigh which would give a probability of the target exceeding  $1000 M^2$  of about  $.7 \times 10^{-3}$  or about .07%.

It is obvious that main lobe jamming at one hop ranges requires only watts of jammer power to mask most aircraft targets.

Side Lobe Jamming at Target Range A broad band high gain antenna in the HF band is likely to have fairly large side lobes as does the present MADRE antenna. Optimistically a mean side lobe level -20 db from the main lobe will be assumed. From the previous section the power level required in the main beam at 1600 miles was about 1.6 watts. This power must be increased by a factor of 100 in order to jam through -20 db side lobes, thereby requiring a total of about 160 watts with an 8 db antenna gain on the jammer.

Standoff Jamming If one assumes that a jammer is located at the far range of a coverage zone (i.e., 1500 miles) and the target is located at the near edge (i.e., 1100 miles) the target signal strength may increase as much as  $\left(\frac{1500}{1100}\right)^4$  or about 3.5 times over what it would be at 1500 miles. In addition the  $F$  factor can be larger or smaller, depending on the ionospheric condition prevailing. If one assumes  $F$  increases by 2 times in a particular case then the added power required of the jammer is 7 times, or about 11.2 watts in the main beam and 1.12 kw to get through the side lobes.

This means in essence that it is entirely practical to jam the radar with one jammer for each few hundred miles in depth by perhaps  $\pm 10$  beamwidths in azimuth, or one jammer per million square miles, with a radiated power of about 1 kw. Conversely a 40,000 square mile area could be protected with a jammer of only 11.2 watts, requiring 25 such jammers per million square miles.

Line of Sight Jamming If the radar station is within line of sight of the jammer (i.e., 200 miles at 30,000 feet altitude) the reduction in range by a factor of 7.5 will increase the jamming power at the radar by a factor of about 50 over what it was at 1500 miles. This value will be modified by the propagation factor in the ionospheric path, making the total jamming stronger by perhaps 5 to 500 times. For the mean value of 50 times the maximum power required would be about 20 watts in the side lobes to mask a 1000 M<sup>2</sup> aircraft into a range of 1100 miles. To mask the target into 550 miles 320 watts is needed, with 8 db antenna gain in the jammer. With a dipole on the jammer 1280 watts would be needed. If the line of sight location were only 100 miles away 320 watts would cover all situations adequately.

For an aircraft to be effective as a jammer at a range of between 100 and 200 miles to mask targets beyond 600 miles he would need about 1 kw of jamming into a dipole. This is a rather major effort as compared to locating several jammers of comparable power but higher antenna gain at one hop ranges.

It is most important, however, to locate the radar beyond line of sight of an enemy territory because a single ground based jammer with an 8 db antenna gain at 100 miles can jam the whole system coverage with a power level of only about 80 watts.

Repeater Jamming Since the MADRE pulses are not coded in any way, and the frequency stability is high, any time synchronized pulse with a constant frequency within the 3 kc pass band of the radar will appear to be a target with a doppler shift equal to the difference frequency between the jammer and the closest harmonic side band of the radar pulse rate. Since the MADRE signal level will be the highest in the HF region a simple filter bank with a threshold setting can select the proper channel and initiate delayed pulse sequences which will gate on the proper stable carrier frequency to simulate any desired false target complex. Power levels of a few watts peak will allow breaking through the side lobes, thereby allowing false target generation over an area of a million square miles from one repeater station. Figure 1 shows a block diagram of the basic intercept and repeater logic required.

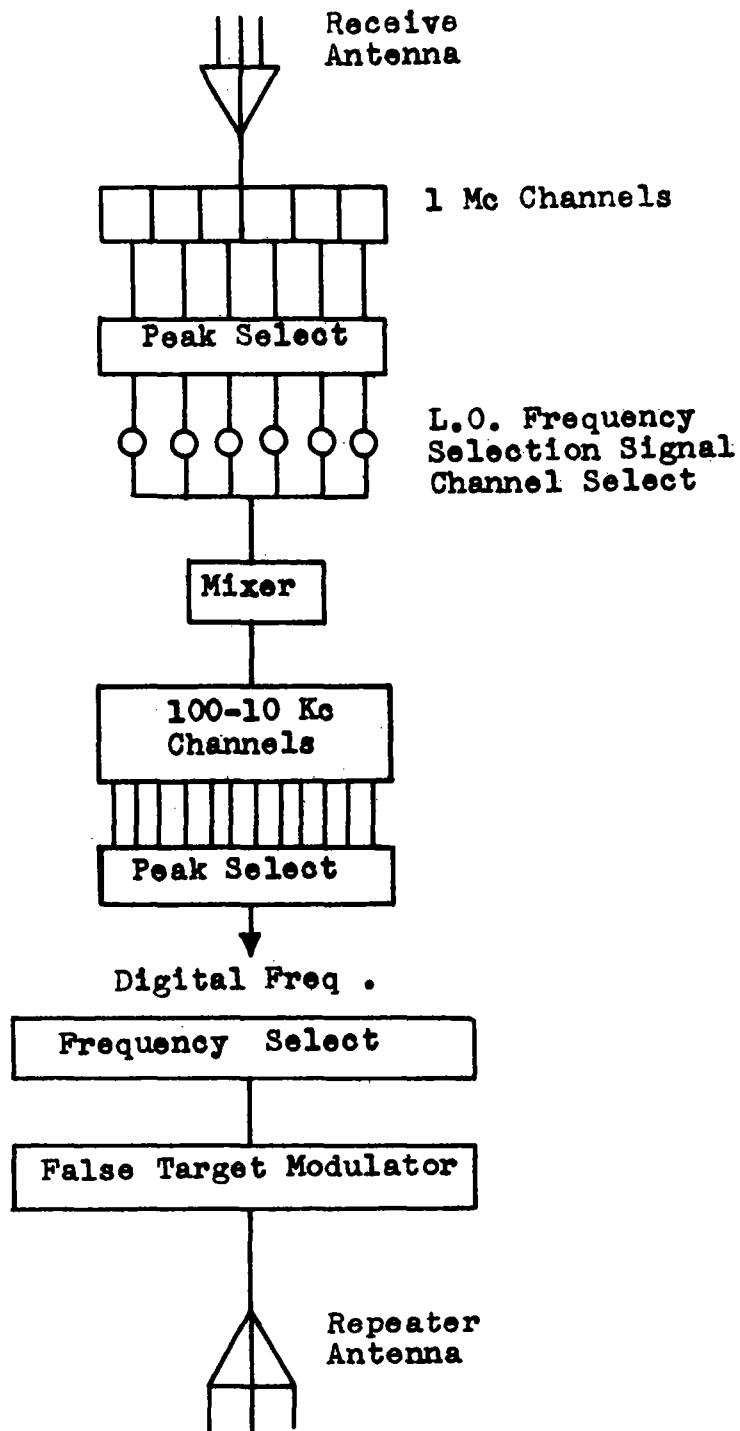


Fig. 1

## APPENDIX D

### EXPANSION AND GROWTH-RESEARCH AND DEVELOPMENT

This appendix discusses possible future additions to the basic system. Implementation would require research and development in some instances and in others application of present knowledge and techniques is possible. Two or more years of investigation and research may be required for determination of value and cost.

### GROWTH POTENTIAL

Introduction The MADRE radar can be implemented in one of two basic ways to achieve its fundamental purpose of detecting aircraft and missile effects at one hop ionospheric ranges. One way, similar to the present MADRE at CRA, uses a single high power transmitter coupled through high power mechanically tuned phase shifters and matching stubs to a phased array antenna. The time required to change frequency is of the order of 15 to 30 minutes; beam direction change is of the order of 5 minutes or less. Mechanical breakdown has plagued the installation but reliability was not purchased in the research installation. A system of this type or one similar using a giant rotating antenna has essentially no growth potential in terms of ECM avoidance or increased data rate. A second way of implementing the system could use a separate broad band transmitter-receiver unit connected to each element of the antenna which combined with a low level beam forming matrix could electronically switch or steer the antenna at rates as high as the pulse repetition frequency, if desired. The cost of the second method is about the same as the first, but all limitations on frequency or beam position rates of change have been eliminated. Interlaced modes of operation can be extremely useful in an operational system of this type. It would be desirable to illuminate certain missile launching sites continuously while maintaining an aircraft search rate adequate for aircraft tracking as well as an interlaced oblique backscatter sounder mode to keep track of optimum frequencies for propagation to the desired ranges. This can be accomplished in an electronically steerable MADRE by subdividing the allowable radar dead time between 0 and 600 naut mi into a number of independent channels. As many as 24-300 microsecond time slots, or 72-100 microsecond slots are available. Each of these can radiate on an independent frequency or group of frequencies and on independent beam positions, increasing the data rate of the system by a factor of 24 to 72, depending only on the amount of total radiated power one wishes to design into the system, and the number of receiver output channels one wishes to provide. Techniques required to accomplish the above types of operation are "state of the art" and are used in various degrees in radars such as ESAR, SPS-33, SPS-48, SRG-59 and others. The optimum programming of a system will be dependent on the exact tactical problem facing the

system at a particular time. This is subject to change, and the programming, for this reason should be flexible and adaptable.

The ECM vulnerability of the basic MADRE integration mode of operation is such that the opposition can deny use of the radar by jamming or spoofing if he so desires. The primary methods the radar can use to reduce vulnerability to jamming are to jump frequency pulse to pulse, use wide band pseudorandom or random frequencies in each pulse or other similar techniques. With proper matched filter processing, coherence and integration efficiency can be maintained and the jamming effort required to subvert the radar can be made to be increased by orders of magnitude. As the sophistication of the radar is increased its cost will rise also. However, if the basic building blocks are designed with the growth potential kept in mind the added cost will be in low level electronic switching and processing devices which are relatively inexpensive compared to the overall system cost.

The following sections suggest design concepts which can allow future growth without replacing basic system elements.

Electronic Programming If one contemplates the utilization of the 7200 microseconds of available time between 0 and 600 naut mi for increased MADRE channel capacity one can visualize as many as 72-100 microsecond time slots, 24-300 microsecond slots, 7-1000 microsecond slots, or any combination of any sizes which adds up to 7200 microseconds. This is a rare ability which shorter range conventional radars are denied because of short minimum range requirement.

A single MADRE channel will use a pulse length of about 300 microseconds. A straightforward extension of data rate can be achieved by transmitting a number of 300 microsecond pulses in sequence, each at a different frequency and independent beam positions. The average power, of course, being increased by the total time duration of the pulses transmitted in the group. Added receiver channels are required for each added transmitted pulse. Doppler processing can be accomplished on multiple channels by using multiple track magnetic drums or equivalent.

Since a variety of operational modes are potentially desirable the time division separation of channels allows great flexibility in choice of interlaced modes of operation.

An electronic programmer can select sequential frequencies from a master frequency source in a pseudorandom, random, or continuous fashion as desired. A filter bank spectrum analyzer can be connected into the frequency generator to inhibit operation on occupied channels. From the above basic starting point possible operating modes become almost unlimited, and the system reaction time to its environment becomes almost instantaneous.

Following is a list of desirable operating modes:

1. MADRE doppler resolution
2. Frequency swept or stepped backscatter sounder
3. Frequency swept or stepped matched filter operation for ECM avoidance
4. Searchlight operation for missile launch observation
5. Tracking channels for continuous tracking of selected targets
6. Double pulse operation for modification of doppler response
7. Coded pulses for communication on a selected beam position.

Since the backscatter amplitude at useable propagation frequencies is at least 60 db greater than the echo from an aircraft the radar energy required for backscatter sounding is only a small fraction of that needed for aircraft detection. Without the use of integration a 300 microsecond pulse could be spread over a band of at least 3 Mc for backscatter sounding with sufficient sensitivity. By use of spectrum inhibiting of occupied channels on both transmitting and receiving, and using a number of matched filters on reception a high resolution backscatter picture can be achieved for all frequencies and all beam directions in a time interval of a few seconds, without interfering with other operating modes of the radar. This mode could be operated continuously or intermittently as experience dictates the need.

Power programing as a function of frequency is probably desirable, since the power required for a given target will be considerably greater on the average at the lower frequencies than at the higher frequencies. This can be accomplished by using shorter integration times at the higher frequencies, or shorter pulses or both. Spread spectrum techniques are more applicable to frequencies above 10 to 12 Mc, because of lesser band occupancy, reduced integration requirements, and less ionospheric dispersion on the average.

The ability to transmit two groups of coded pulses with identical mean frequency and therefore identical phase versus range during one 7200 microsecond period allows a modification of the doppler response curve upward by a factor of 4:1 or more which can be of great value in resolving radial velocity of missile and satellite type targets. This ability can be implemented with a pair of matched filters for reassembling the coded pulses for phase comparison. With this feature a non-ambiguous

range of 2500 miles can be obtained with a basic pulse rate of 32 per second with the doppler response determined by either the pulse rate interval, or the coded pulse separation within one transmit interval.

Since ideally MADRE would like to communicate filtered information with small time delay to its information users one channel could be directed as desired and transmit intelligence on a coded pulse at the optimum frequency with only a small fraction of the total power. A repeat back system time synchronized could close the message loop.

Without further amplification of details it is seen that MADRE expansion capability from one to as many as 24 or more channels can be done by added electronic programming devices and added power. With this potentially available capability an extremely versatile high data rate high ECM resistant system could ultimately result, the features being added step-wise as needed.

Spread Spectrum Techniques Any of a considerable variety of pulse coding techniques allows the transmission of a broad frequency spectrum on a long pulse which, when passed through a matched filter coherently reassembles the components into a short pulse of high amplitude. This class of techniques preserves coherence and the ability to resolve doppler shifts, at the same time increasing range resolution. For a given pulse energy the spread spectrum technique increases the jamming power required by the compression ratio, other factors being equal.

Two basic problems must be faced in the use of any spread spectrum at HF frequencies. First the instantaneous band occupancy average varies from as high as 80% between 5 and 10 Mc to about 50% from 12 to 20 Mc to perhaps 10% or less above 20 Mc. Second, the dispersion of the ionosphere as a function of frequency will provide a variable limit on the bandwidth which can be transmitted. Experiments run by the Bureau of Standards with 20 microsecond pulses show no pulse distortion over a 2300 km path from Boulder to Sterling with proper choice of frequency and show only two well defined pulses of variable spacing over a wide band of frequencies for the ordinary and extraordinary ray paths. The Canadians have developed a pulse coding method for HF using 10 microsecond pulses with success. A look at a great number of ionograms shows that usually frequency bands are available showing little dispersion. This leads one to believe that under most conditions even wider spectrums than 100 kc can be used without serious difficulty.

The problem of band occupancy is more severe, and this must be faced head on by designing an analysis system which transmits and receives energy in the unoccupied bands only. Since a matched filter can consist of a bank of narrow frequency bandwidth filters whose outputs are added together through appropriate delay networks it is possible to make the receiving system automatically look only in the unoccupied channels either by built-in frequency-by-frequency limiting, or by inhibiting the occupied frequency

segments from a master filter bank analyzer. The matched filter system will work with a small percentage of the total channels if the disposition is random. However, something approaching 50% would be desired for good efficiency. However, the spread spectrum technique is still feasible with a very limited number of frequencies by non-coherently summing the outputs from fewer channels, using larger pulses per channel. This mode is useful for ECCM, but does not result in coherent pulse compression.

The simplest spread spectrum technique is by use of a linear FM pulse (chirp). Pseudorandom codes have been developed for some applications and are more resistant to spoofing and analysis. Completely random codes are the most sophisticated, and can be accomplished by electronic switching of the matched filter by the random transmission.

Pulse compression ratios using spread spectrum techniques of 1000:1 are considered state of the art. Ratios of 100:1 can be accomplished more easily. Research should be undertaken to determine the optimum parameters for use of this principle at HF.

Research and Development Areas Since the development of solid state electronics, highly sophisticated electronic programing, computing, and analysis has become commonplace in military radar systems, requirements for particular applications are often met by assembling the appropriate standard building blocks into the desired configuration. Research and development in this area is primarily that of determining the system requirements and procuring the equipment in the desired form factor.

Since antennas and transmitters have resisted efforts toward miniaturization (except for use of frequency scaling for experimental work) research in this area requires design and construction of considerable hardware with the possibility of pitfalls and need for fresh starts along the way. For this reason it is desirable to try several likely approaches in parallel in order to improve the chances for success, and to allow choice of the best proven solution in time to meet a delivery schedule.

Choice of final system configuration can be strongly dependent on the choice of antenna type and choice of transmitter power and bandwidth may be dictated by antenna performance.

For example, if a suitable antenna cannot be developed for a frequency range of more than 1.8 to 1 in frequency, then one must consider using three antennas to cover the frequency range. If each element in each of the antennas must be driven with a transmitter, then the required transmitter power and bandwidth will be a function of which antenna it feeds. Or the optimum might consist of one transmitter switched between elements of each antenna. In any case, the final transmitter requirement will be based on the optimum antenna solution.

The radar requirement is basically to detect and track certain types of targets over a specified area in the presence of large backscatter echoes from the surface of the earth. Optimization of parameters to maximize the probability of maintaining tracks on the maximum number of targets is a research area in itself, the best balance between azimuth resolution, range resolution and velocity resolution is dictated by factors which are not well known at the present time. The cost of either extremely high velocity resolution or extremely high position resolution is in increased data intervals or increased channels to provide parallel channel operation. An increase in range resolution by 30 to 1 will improve sub-clutter visibility by this amount. A reduction of velocity resolution from one knot to 10 knots will increase data rate by 10 to 1. A reduction in beamwidth will improve sub-clutter visibility, radar range and azimuth accuracy, but will require more beam positions to scan and so will reduce data rate. A fast scan rate with track memory will provide enhanced sensitivity to moving targets and will reduce false indications from meteors and clutter because of the development of unique signatures for desired targets. Optimization in the above areas required a flexible radar combined with operational research of a continuing nature.