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MADRE PERFORMANCE

PART 1 - OBSERVATIONS OF JANUARY 18 AND 25, 1962

[UNCLASSIFIED TITLE]

F. M. Gager, W. C. Headrick, G. A. Morgan,
F. H. Utley, and E. N. Zettle

Radar Techniques Branch
Radar Division

December 31, 1962



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14 NRL ~~Report~~ 5862

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PART 1 - OBSERVATIONS OF JANUARY 18 AND 25, 1962

[UNCLASSIFIED TITLE]

**VERY-LONG-RANGE, OVER-THE-HORIZON DETECTION
OF AIRCRAFT WITH THE MADRE RADAR**

PART 1 - OBSERVATIONS OF JANUARY 18 AND 25, 1962

[SECRET TITLE]

F. M./Gager, W. C./Headrick, G. A./Morgan,
F. H./Utley, and E. N./Zettle

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31 December 1962



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ABSTRACT
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The Madre radar, which utilizes matched backscatter rejection filters, signal integration by magnetic storage, and high resolution doppler discrimination, has been used to detect transatlantic air traffic via an over-the horizon mode. Detections of aircraft have been accomplished in the range 800 to 1800 nautical miles with only fair ionospheric propagation conditions prevailing. Discontinuous observations have evidenced the firm capability of target location prediction with intermittent operation.

PROBLEM STATUS

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

AUTHORIZATION

NRL Problem R02-23
Project R' 001-02-41-4007

Manuscript submitted October 24, 1962.

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VERY-LONG-RANGE, OVER-THE-HORIZON DETECTION OF AIRCRAFT WITH THE MADRE RADAR

PART 1 - OBSERVATIONS OF JANUARY 18 AND 25, 1962

[Secret Title]

INTRODUCTION

The Madre radar and its forerunner, the Music radar, are research radars which were developed to provide sufficient scientific data from which firm specifications for an over-the-horizon operational radar could be set down. Thus a research radar is conceived to be without certain features which an operational type should contain, though of sufficient flexibility and facility to provide basic research data. The Madre radar is an MTI radar with the capability of 1 to 2 knots resolution. It operates in the high-frequency band, 13.5 to 27.0 Mc. The Music and Madre radars have been detailed previously (1, 2). The results of varied investigations incidental to both systems are covered in other reports listed in the bibliography.

The Music radar and the low-powered Madre radar, placed in operation in 1954 and 1958 respectively, have been successful in detecting at great distances, and in real time, atomic explosions and missile punctures of the ionosphere (3-5). A high-power extension of the low-powered Madre radar was first placed in operation at NRL's Chesapeake Bay Annex in August 1961. As with all research systems containing many developmental unknowns, there is a shakedown period, still in progress. However, it was decided, when the system became available, that attempts would be made to detect moving targets at very long ranges over the horizon.

During the evaluation period of the low-powered Music and Madre radars, 1954 to early 1961, it became evident that a number of important military targets were susceptible to detection with this type of radar: aircraft, airbreathing missiles, missiles at or near takeoff, and missile and atomic-blast punctures of both the ionosphere and subionosphere areas. One of the most difficult targets to detect of those listed is an aircraft, and it is shown that success in this area almost guarantees success with the others. It is the purpose of this report to disclose some early aircraft-detection work and representative other work of the same type in the general field of the targets enumerated.

BEACON-TRANSPONDER FLIGHTS

Beacon transponders were placed aboard NRL aircraft, an R5D and a WV2, and some controlled-flight experiments were conducted. A flight in the period August 28 through September 1, 1961, with the NRL R5D aircraft, registered a number of probable detections of the skin of the aircraft at very great distances. The faster aircraft, the WV2, was deemed more detectable because it provided a doppler which was easier to handle with the Madre equipment and with the sometimes necessary lowest frequency of operation.

On September 5, 1961, it was possible to detect the skin of a WV2 aircraft enroute from Puntarenas Naval Air Station to the Azores, on three separate frequencies: 13.68 Mc, 18.036 Mc, and 23.1 Mc. Attempts to employ 26.6 Mc at or near the end of the flight were unsuccessful because the skip zone illuminated was beyond the Azores and therefore not useful.

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for that time and date. The target returns from the skin and transponder were first detected on 13.68 Mc at a slant range of 850 naut mi, and these were tracked for several minutes. Existing propagation conditions and equipment characteristics dictated a shift in frequency to 18.036 Mc. Upon shifting the frequency, and after the aircraft had entered the illuminated zone, tracking was accomplished for about 45 minutes and for slant ranges of 1500 to 1700 naut mi. Another shift in frequency, to 23.1 Mc, allowed tracking of the WV2 plane to 1800 naut mi.

Figure 1 shows nine Madre primary display pictures taken during the time of operation on 18.036 Mc. This display shows doppler frequency vertically and range interval horizontally. The range intervals 0 to 450 naut mi, 450 to 900 naut mi, 900 to 1350 naut mi, and 1350 to 1800 naut mi are folded, but knowledge of the correct range is obtained by repetition-rate manipulation, an examination of the extent and range of the illuminated area, and position communications with the aircraft itself. The doppler scale is about 0 to 45 cycles, with zero doppler set at the bottom of the scale. It should be stressed that these pictures were made from a replay of the magnetic-taped radar i-f, and they are not as good as the event seen in real time on the Madre displays. In addition, there is some noise and range and doppler drift in the magnetic-tape playback. In Fig. 1 the returns from the beacon are labeled B and those from the skin of the aircraft T. Position identification of the controlled target, among other targets, is effected by noting that target and beacon proceed together with a constant time (range) delay and constant doppler difference.

Any interpretations from the beacon-transponder flight of September 5, 1961, should be made with the knowledge that the propagation condition was "poor-to-fair" on the initial part of the flight and "fair-to-good" toward the end of the flight.

During the period between this flight and those to be reported subsequently, much experience has been gained with the system, while its reliability as well as its capability have been improved. Means were also added to quantify, wherever possible, some of the qualitative information disclosed, so that some measure of target size might be set at reasonable bounds.

DETECTION OF AIRCRAFT TARGETS OF OPPORTUNITY

The next groups of targets to be discussed are aircraft in an illuminated area along the great-circle path from the east coast of the United States to Europe in the range 450 to 1800 naut mi. The data cover two representative days more recent than those reported with beacon transponders and provides some measure of detection capability without transponder identification. To be sure, there are often more targets than one operator can handle, so the data presented are for those chosen by the operator. The equipment used in these measurements provides range rate and range of a selected target. The range-ambiguity situation for this series of detections was much simplified by operating at a 90-cycle repetition rate, with the first and third 450-mile range gates blanked out. In this manner, possible detections were in the ranges 450 to 900 naut mi and 1350 to 1800 naut mi. This facility materially cleared up the display screen by eliminating all local targets in the first 450 naut mi. Thus all detected targets had to be over the horizon at the operating frequencies reported, because the horizon ray is at about 100,000 feet at a range of 450 naut mi.

Figure 2a is a ray-path plot of the upper and lower rays, indicating the illumination of the earth's surface. Figures 2b and 2c are actual i-f A-scope photographs taken on January 18, 1962, and January 25, 1962, respectively, with the transmitter temporarily set at a repetition rate so that 3600 naut mi is displayed horizontally.

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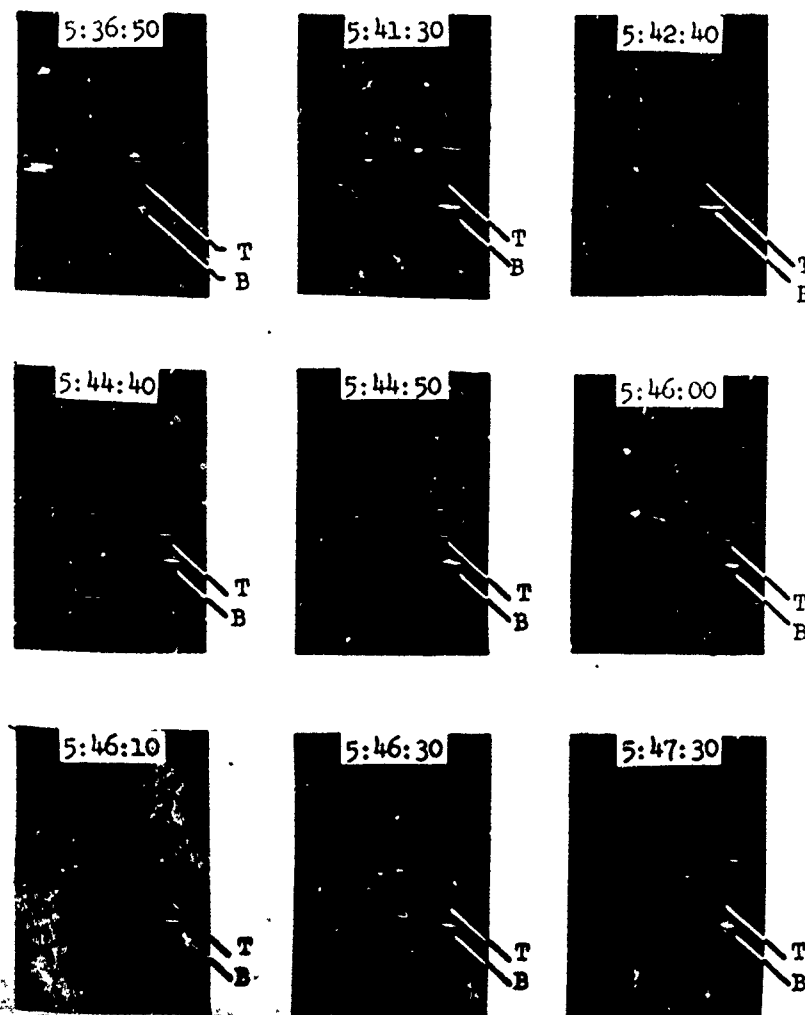


Fig. 1 - Madre range vs range rate display showing simultaneous echoes from airborne beacon (B) and its aircraft carrier (T)

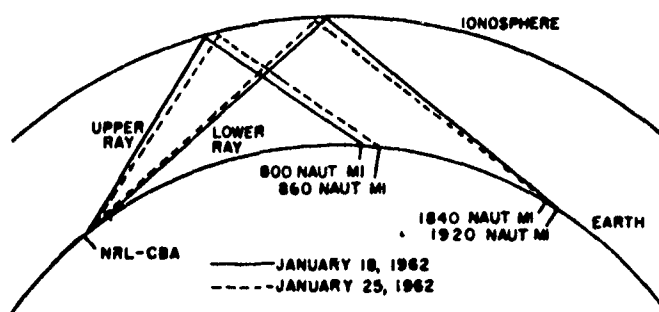


Fig. 2a - Approximate ray paths. Solid lines indicate propagation on January 18, 1962; dotted lines indicate propagation of January 25, 1962.

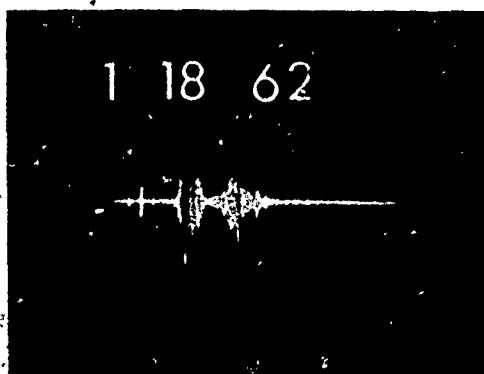
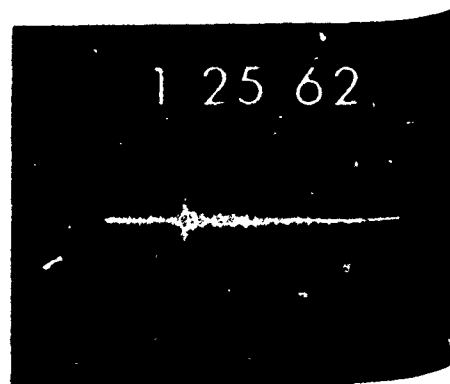


Fig. 2b - Amplitude vs range film record showing meteor, calibrating signal, and backscatter (800 to 1920 naut mi) for January 18, 1962

Fig. 2c - Amplitude vs range film record showing backscatter (860 to 1840 naut mi) for January 25, 1962



With this condition of surveillance, any aircraft detected had to be more than 800 naut mi away and, therefore, over the horizon. Two possible ranges existed, due to range fold-over, for some targets on January 18, 1962, either the 800 to 900 naut mi sector of the 450 to 900-naut-mi range gate, or the whole 1350 to 1800 naut mi target gate. On January 25, 1962, the detected aircraft had to be from 1350 to 1800 naut mi, since the backscatter started at approximately 860 naut mi, and little or none of the first 450- to 900-naut-mi range was viewed.

For the series of detections to be described subsequently, the equipment was set for a minimum detectable signal of 0.04 microvolt (rms) at the receiver terminals, the backscatter signal strength which is subsequently removed by the comb filters being up to several millivolts at the receiver terminals at the same time. The data were taken with 100 kw average power, with the broadside-array antenna, 17 to 23 db gain, beamwidth 15 to 8 degrees.

When a detection was selected and followed, four elements of data were cyclically recorded or observed whenever possible:

1. The slant range to the target.
2. The range rate of the target.
3. An assessment of the target's relative signal strength during the preceding minute on a 0-4 scale, on which 0 is no return, 1 is weak, 2 is fair, 3 is strong, and 4 is very strong (3 is an input signal of 0.3 to 0.4 microvolt).
4. The signal amplitude in microvolts at the receiver terminals. The backscatter range from the illuminated ground, Figs. 2b and 2c, was checked to make sure the illuminated path did not change appreciably during observations.

It is emphasized that the Madre research equipment is still under development. On January 25, 1962, for example, the scientists experienced 27 minutes of down time due to equipment problems in 190 minutes of operation. An additional 20 to 25 minutes were also expended to adjust the equipment for special measurements. Therefore, none of the aircraft were under surveillance continuously during the observation periods on January 18, 1962, and January 25, 1962, but it is of interest to note that a track can be picked up after interrupted operation.

The ranges to the target are all slant ranges. True over-the-ground ranges will be shorter by about 50 naut mi for the longer ranges and 100 naut mi for the shorter ranges due to the rays traveling to the ionosphere and then down to the target. Also, all radial speeds recorded will be below the true radial ground speed due to the reflection angles involved. The fact that the aircraft's flight path may not be on a radial to the radar station is also of consequence. Techniques are known and often employed to correct range and range rate so as to provide operational data. Any system of such radars would, of course, combine data from at least two sites to provide ground speed and course immediately.

EXPERIMENTAL DATA

January 18, 1962, Observations

The Bureau of Standards Central Radio Propagation Laboratory measured the propagation characteristics of the North Atlantic path as index 5 for the hours 0600-1200 and index

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for the hours 1200-1800; in consequence, the data for January 18, 1962, were taken under fair to fair-to-good propagation conditions. On January 18, 1962, the high-power equipment was set up on 16.17 Mc for aircraft-detection measurements, and target observations started at 1145 EST. At 1147 the first target was selected for observations. The range to this target was observed at 648 naut mi, which, since the ground return did not start until 800 naut mi (Fig. 2a), meant that the target was actually at 1548 naut mi and subsequently was followed to a range of 1780 naut mi. This track of real-time detection of the preceding target is shown in Fig. 3a. The circles designate the observed range and the crosses designate the predicted range from the last observation. It is interesting to note that the difference between predicted and observed range for this plot is never greater than 24 naut mi. The solid line on the chart is the predicted range path from the first observation. It is noted that this line differs by only 16 naut mi from the observed range 234 naut mi later.

Figure 3b shows the relative signal strength vs time of the signals (Fig. 3a) on the 0-4 signal-intensity scale discussed under experimental procedures, where the solid zero line represents no signal. Where the zero line is broken, observers were unable to take data due to equipment adjustments, companion measurements, or equipment problems.

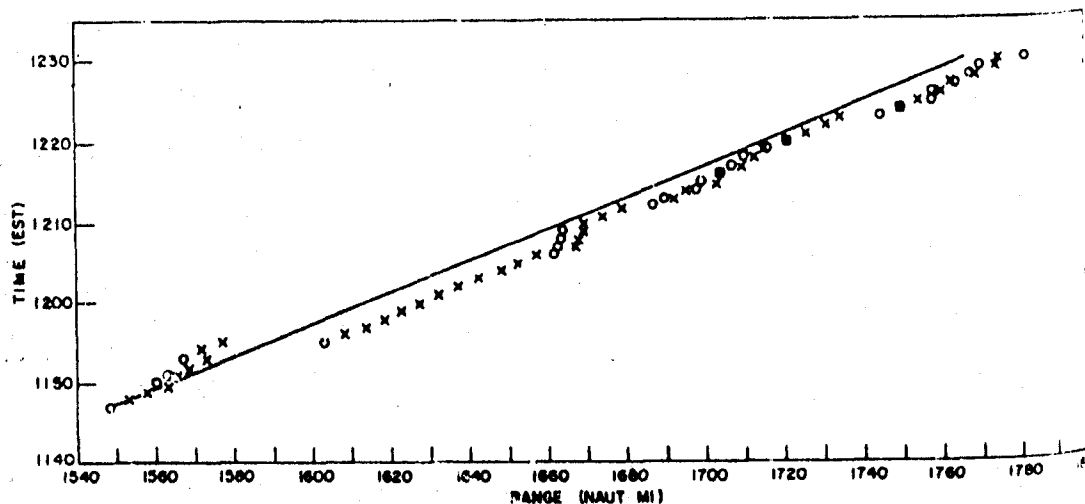


Fig. 3a - Time vs range plot for aircraft of opportunity of January 18, 1962, with the observed radial velocity varying from 292 to 311 knots

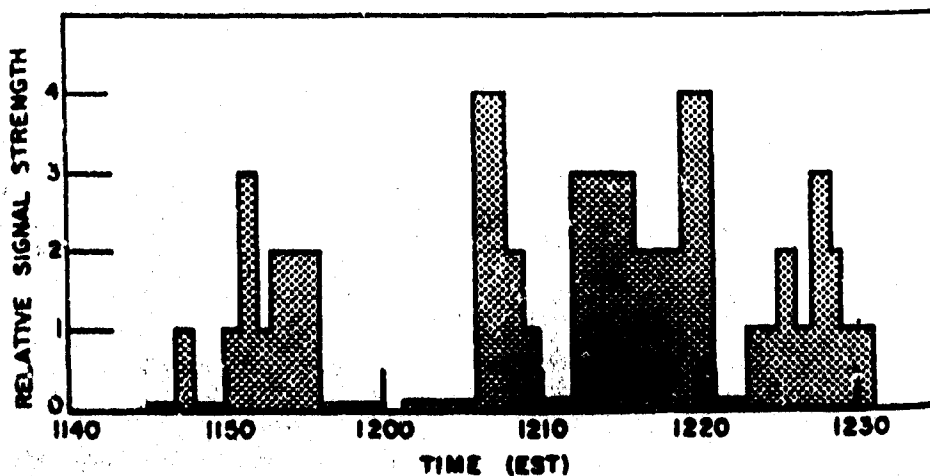


Fig. 3b - Relative signal strength vs time plot for the aircraft target of Fig. 5

Another target, an approaching one, was chosen at 1151 EST, January 18, 1962, at a range of 850 naut mi, and was tracked until 1210 EST to a range of 759 naut mi, when it left the illuminated region of possible detection. The time vs range track of this approaching target is shown in Fig. 4a; relative receiver input signal intensity vs time for this track is shown in Fig. 4b. The dots, crosses, and full line have the aforementioned significance. This target apparently flew through the leading edge of the backscatter area and thus cut out very sharply, in contrast to the first target (Fig. 3a), which flew out beyond the observation range at about 1800 naut mi. The maximum predicted relative range error for this target is 19 naut mi, and the relative error is observed to be 16 naut mi on last detection from the position predicted by the first instant of detection.

Another approaching target was selected at 1155 EST on January 18, 1962, at an indicated slant range of 1689 miles and a radial speed of 395 to 397 knots. This target was tracked and the receiver input signal measured for 10 minutes before losing it. It could be assumed that this target was a high-speed aircraft flying at an angle across the illuminated area of the beam. The time vs range plot for this target is shown in Fig. 5a, and relative signal intensity vs time is given by Fig. 5b. The predicted relative range error for this target is 14 naut mi, and the error on prediction from first detection about 19 naut mi.

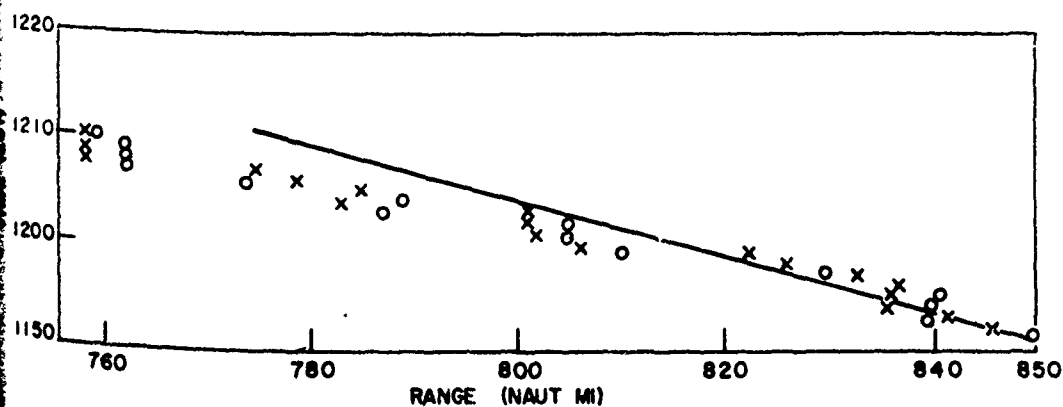
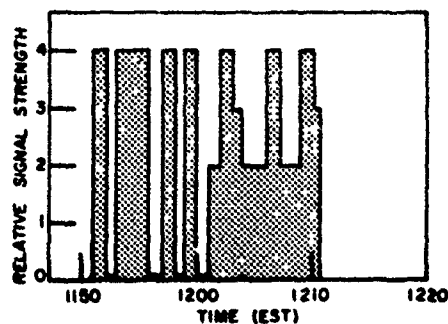


Fig. 4a - Range vs time plot for aircraft of opportunity of Jan. 18, 1962, with the observed radial velocity varying from 229 to 233 knots

Fig. 4b - Relative signal strength vs time plot for the aircraft target of Fig. 7



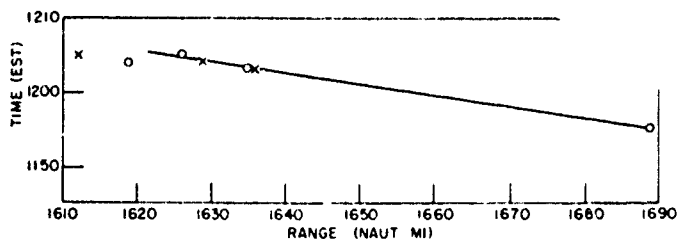


Fig. 5a - Range vs time plot for aircraft of opportunity of Jan. 18, 1962, with the observed radial velocity varying from 395 to 397 knots

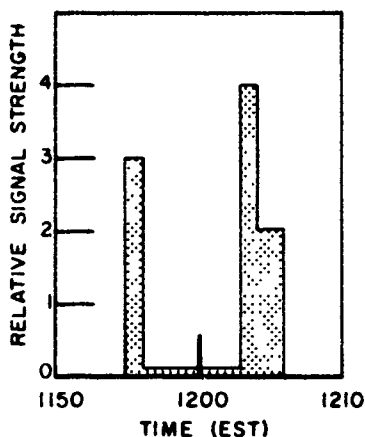


Fig. 5b - Relative signal strength vs time plot for the aircraft target of Fig. 9

After data were taken on these three targets, equipment adjustments were made; another target was selected at 1313 EST at 761-naut-mi range and 297 to 311 knots radial speed. The observations made on this target started at 1313 and ceased at 1316 when equipment was readjusted for another type of observation. A time vs range plot is shown in Fig. 6a, with relative signal amplitude vs time in Fig. 6b.

January 25, 1962, Observations

The Bureau of Standards Central Radio Propagation Laboratory measured the propagation characteristics of the North Atlantic path as index 4 for the hours 0600-1200 and index 7 for the hours 1200-1800; in consequence, the data for January 25, 1962, were taken under poor-to-fair and good ionospheric conditions. The January 25 observations of aircraft of opportunity started at 1113 EST, with the transmitter operating on 16.17 Mc. The target selected was observed to be receding at 1117 EST at a range of 1290 naut mi and was tracked to 1567 naut mi at 1204 EST, when it disappeared from the indicator. Fig. 7a is a plot of time vs range for this target, and Fig. 7b is a plot of relative signal intensity vs time. It is noted that the maximum predicted relative range error is 29 naut mi; the predicted distance from the first observation extrapolated to the last indicates a relative range error of 55 naut mi.

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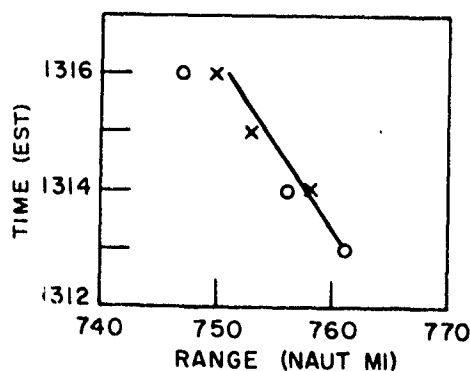
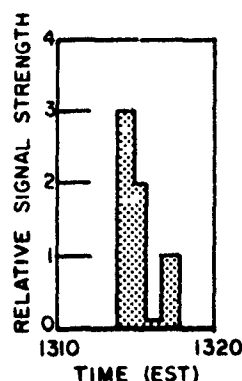


Fig. 6a - Range vs time plot for aircraft of opportunity of January 18, 1962, with velocity variable from 297 to 311 knots

Fig. 6b - Relative signal strength vs time plot for the aircraft target of Fig. 11



The next target chosen was observed at 1235 EST at a range of 1422 naut mi and a radial speed variable from 281 to 293 knots. This target was tracked to 1689 naut mi at 1328 EST. At this time another observer took over the indicator for observation of still another category. The range of this target at last detection predicted from first detection was 1678 naut mi, while the range measured was 1689 naut mi, giving a predicted relative range error of 11 naut mi. The time vs range plot for this target is shown in Fig. 8a, and the relative signal intensity vs time is shown in Fig. 8b.

Another target was selected at 1300 EST at a range of 1351 naut mi and a radial speed of 526 knots. The predicted range to the next observation 8 minutes later is 66 naut mi, raising some question as to whether the first point and the remaining data are the same target or whether the target turned slightly during the period of no observation. The predicted range from this observation to 1328 EST is in error 18 naut mi, while the predicted relative error from the second observation to the last is 9 naut mi. The observed radial velocity in the observation period was 526 to 534 knots. The Madre equipment was operating for this period to show range out to about 1700 naut mi, so the termination of this track at approximately 1680 naut mi is reasonable. The signal-strength indications were such that one could possibly observe this target farther out on its course by a shift in operating frequency. The time vs range plot for this target is shown in Fig. 9a, and the relative signal intensity vs time in Fig. 9b.

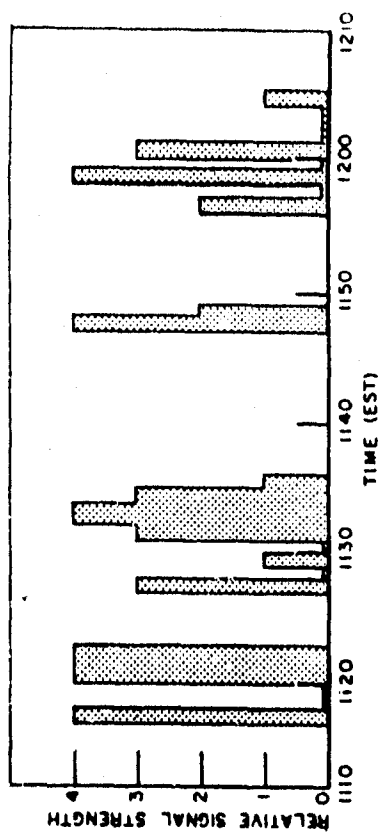


Fig. 7b - Relative signal strength vs time plot for the aircraft target of Fig. 7a

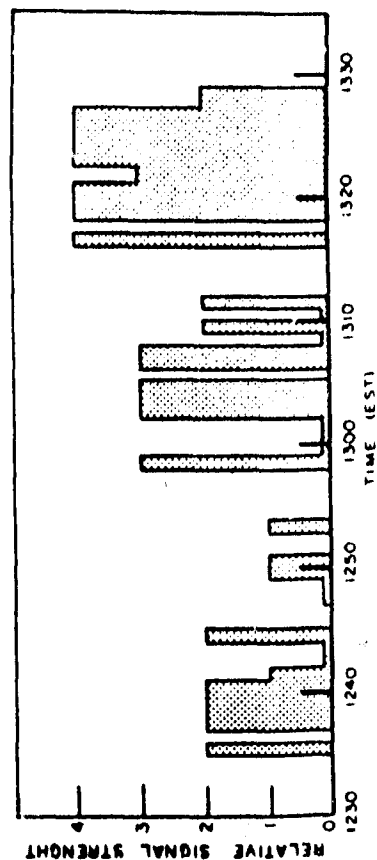


Fig. 7c - Relative signal strength vs time plot for the aircraft target of Fig. 7a

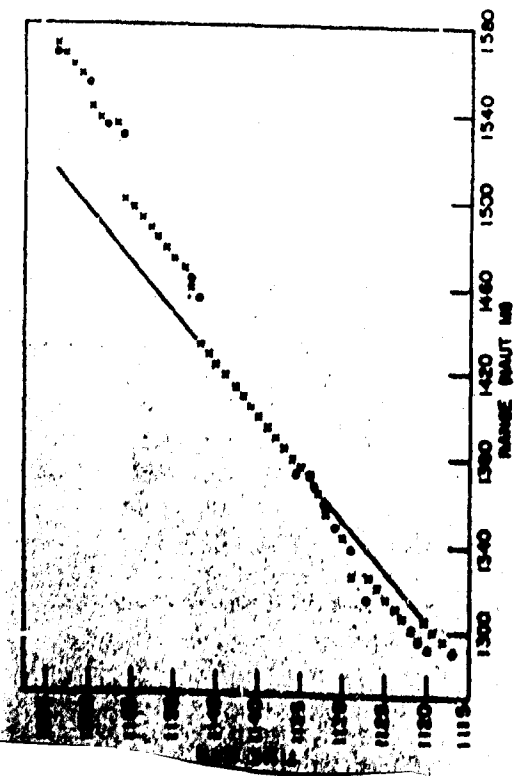


Fig. 7a - Range vs time plot for aircraft of opportunity of January 25, 1962, with the observed radial velocity varying from 283 to 297 knots

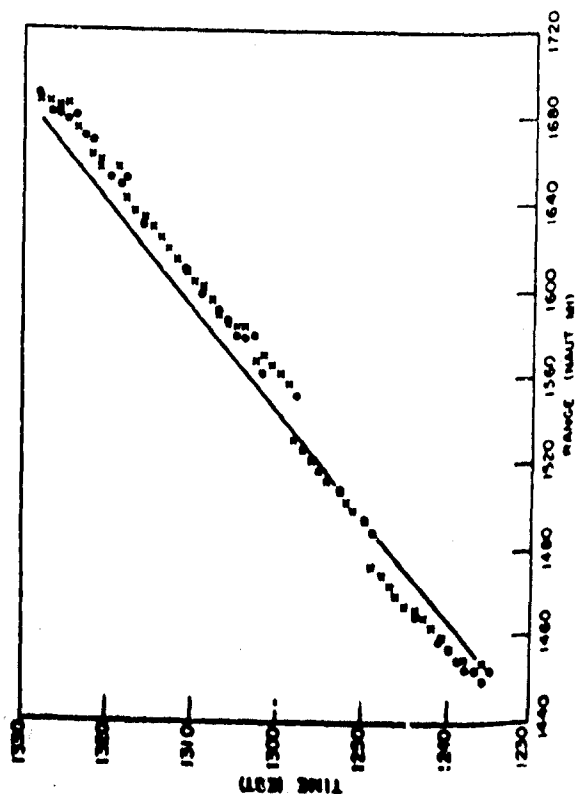


Fig. 7d - Range vs time plot for aircraft of opportunity of January 25, 1962, with the observed radial velocity varying from 283 to 297 knots

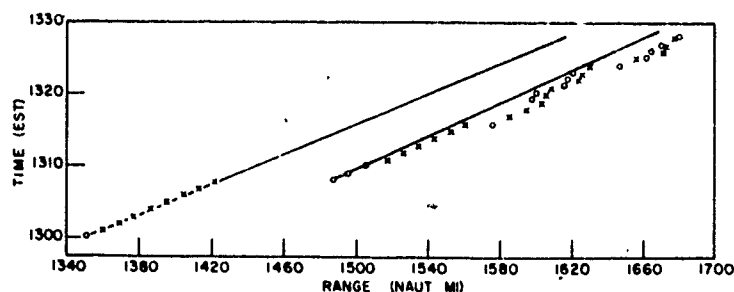


Fig. 9a - Range vs time plot for aircraft of opportunity of January 25, 1962, with the observed radial velocity varying from 526 to 554 knots

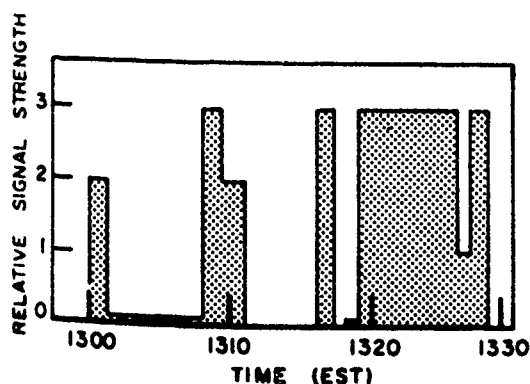


Fig. 9b - Relative signal strength vs time plot for the aircraft target of Fig. 9a

Still another target was observed at 1327 EST at a range of 1393 naut mi, with a radial speed variable from 331 to 337 knots. This target was tracked until 1420 EST out to 1681 naut mi. The predicted range at 1420 EST from the observation at 1327 was 1691 naut mi, with a relative range error of 10 naut mi. The time vs range plot for this target is shown in Fig. 10a, and the relative signal intensity vs time in Fig. 20.

FUTURE PLANS

At this writing it should be stated that detections of both beacon-transponder flights and numerous targets of opportunity have been accomplished, in addition to those herein reported, with gratifying results. Plans are to continue observance of such flights over the immediate period of months, and to obtain flight-strip records from the Federal Aviation Agency, New York Oceanic Control, and Canadian Department of Transport, Gander, N.S., Control Center, to assist in identifying the aircraft tracks. It is also planned to increase the capability of the Madre system during this period. Chief among these improvements for aircraft detections is the addition of other comb-filter notches to allow lower repetition rates of operation to provide other choices of 450-naut-mi range. As a matter of interest, the surveillance program with the Madre radar directed toward the detection of events from the Atlantic Missile Range will be provided with acceleration gates tailored to the AMR events. This capability added to velocity gates will materially assist in the quantitative data being accumulated. Wherever possible, future reports of this type will include the received signal level for those who desire to make further computations.

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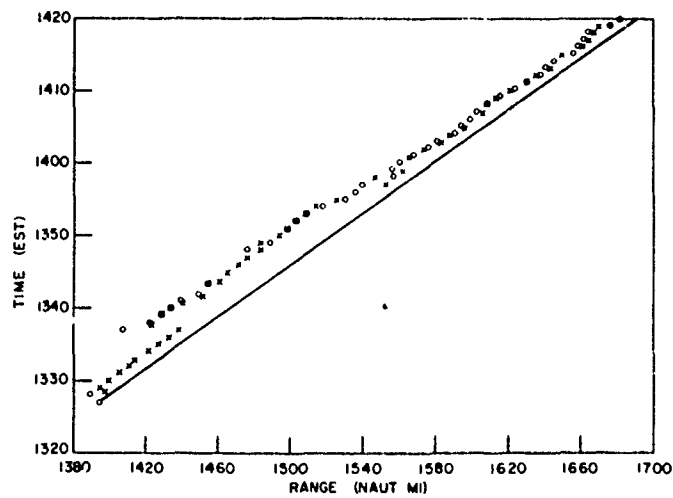


Fig. 10a - Range vs time plot for aircraft of opportunity of January 25, 1962, with the observed radial velocity varying from 331 to 337 knots

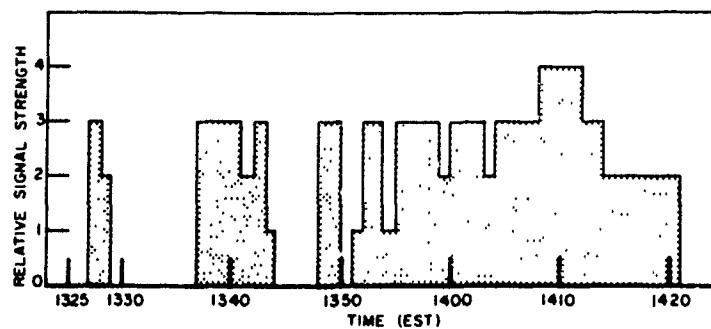


Fig. 10b - Relative signal strength vs time plot for the aircraft target of Fig. 10a

CONCLUSIONS AND REMARKS

1. It is evident from the content of this report that, given an ionospheric path and a target in the beam, the Madre radar can detect aircraft targets at least out to ranges of 1800 naut mi. At this range, signal strengths are often sufficient for one to expect longer ranges of detection.
2. The observed ranges over several hundred miles of flight path compare very well with the predicted ranges.

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3. This work shows the advisability of making many such detections under varying conditions in order to specify the nature of equipment characteristics for an operational radar of a system of such radars.

4. The disclosures in this report also show the advisability of using means for determining immediately whether a target is approaching or receding at the instant of detection. The nature of this equipment is known and preparations are underway to demonstrate this feature.

5. Aircraft of the type detected and reported herein present a target cross section of 10^2 to 10^3 square meters at high frequency.

6. It is concluded that over-the-horizon detections can be made with ionospheric conditions as degraded as "fair."

7. The relative signal-intensity scale is not linear. Also, where the signal intensity-time charts show zero signal level (heavy line), it should not be concluded that the target was absent for the full minute. When several targets are cyclically observed and the signal level is recorded as zero at the appointed time for measurement, it is recorded as zero even though it may have been present before or after the appointed measurement time.

ACKNOWLEDGMENT

The authors acknowledge the efforts of the personnel who observe the data and keep the equipment in operable condition. In this respect the excellent work of the Section Heads, Messrs. F. E. Boyd, J. M. Headrick, and G. K. Jensen, is specifically acknowledged. In addition, the observation work of Mrs. C. B. Tesauro and Messrs. S. R. Curley, J. L. Ahearn, W. B. Patton, M. S. Lieberman, D. C. Rohlf, G. A. Skaggs and E. W. Ward is commended.

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MADRE PERFORMANCE. PART 1 - OBSERVATIONS
OF JANUARY 18 AND 25, 1962 [Unclassified Title], by
F. M. Gager, W. C. Headrick, G. A. Morgan, F. H.
Utley, and E. N. Zettle. 20 pp. and figs., December 31,
1962.

The Madre radar, which utilizes matched back-
scatter rejection filters, signal integration by magnetic
storage, and high resolution doppler discrimination, has
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MEMORANDUM

20 February 1997

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