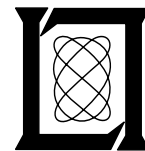


Comparison of the Performance of the Moving Target Detector and the Radar Video Digitizer

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COMPARISON OF THE PERFORMANCE OF THE MOVING TARGET DETECTOR AND THE RADAR VIDEO DIGITIZER

I. INTRODUCTION

Use of primary radar data in the FAA automated air traffic control system has been impeded by the inability of existing signal processors to reliably detect aircraft in regions of strong ground and precipitation clutter, particularly when aircraft are moving tangentially to the radar. During the past three years, under FAA sponsorship, M.I.T. Lincoln Laboratory has developed new techniques which significantly enhance automated aircraft detection in all forms of clutter. These techniques are embodied in a processor called the Moving Target Detector (MTD) which has been evaluated at the FAA National Aviation Facilities Experimental Center (NAFEC), Atlantic City, N.J. This processor employs coherent linear doppler filtering, adaptive thresholds and a fine grained clutter map to reject all forms of clutter simultaneously. A complete description of the MTD and the experimental apparatus used in the evaluation tests is given in Reference 1.

Also under FAA sponsorship, the Burroughs Corporation and Univac have continued development of the Radar Video Digitizer (RVD) series of noncoherent digital processors. The most recent version of this approach is the RVD-4. The MTD and RVD-4 processors have been integrated into the ARTS-III system at NAFEC and their performance compared during a set of test flights carried out during the summer of 1975.

The purpose of these comparison tests was to confirm the relative performance of the MTD and the RVD-4 radar processor in automated radar control systems. Measurements included:

- (1) False alarm and detection statistics using calibrated, coherent signal generators.
- (2) MTI improvement factor and radar sensitivity in the presence of ground and weather clutter.
- (3) Blip-scan ratios and position reporting accuracies in flight tests using controlled aircraft flying in various clutter environments.

This report presents a detailed comparison of the performance of both radar processors.

II. SUMMARY

A. Test Facilities and Instrumentation

The MTD and the RVD-4 were integrated into an ARTS-III system at NAFEC and simultaneously tested during the summer of 1975 under a variety of clutter conditions. The MTD was operated with an FPS-18, a coherent S-band radar with parameters nearly the same as those of the ASR-8, while the RVD-4 was operated with an ASR-7 transmitter. The sensitivity of the ASR-7 and FPS-18 were adjusted so that both systems had equal signal-to-noise ratio per scan in receiver noise. During these tests the FPS-18 and ASR-7 were operated using the same antenna, in this case an ASR-4 antenna. A block diagram of the test setup is presented in Figure II-1. Tests included measurement of MTD/RVD-4 detection performance on controlled aircraft flying in the clear, in heavy precipitation (rain level up to 40 dB above noise level) and over ground clutter near Atlantic City, New Jersey. Subclutter visibility measurements were also made using a coherent test target generator. Data consisting of radar reports, beacon reports, radar/ beacon correlated reports and track reports for the MTD and RVD-4 processor were recorded on magnetic tape as shown in Figure II-1 for subsequent analysis using interactive display techniques developed at Lincoln Laboratory (see Reference 1).

B. Performance in the Clear

The probability of detection vs IF signal-to-noise level of the sensor/processor systems employing the MTD and RVD-4 was measured (using a coherent test target generator) and found to be equal. In addition, controlled aircraft were flown in clear regions and the simultaneous blip-scan ratios measured. The detection performance of the two sensor/processors was the same to within statistical uncertainties, verifying that the two systems had been properly equalized. Also, both systems were shown to have adequate false alarm performance in clear regions. Careful measurement of the range and azimuth accuracy of both systems using 100 aircraft tracks, (of range varying between 5 nmi and 35 nmi, and of altitude varying between 300 and 25000 feet,) demonstrated that the MTD radar report data was accurate in azimuth to 0.14 degrees, while the RVD-4 report data was accurate

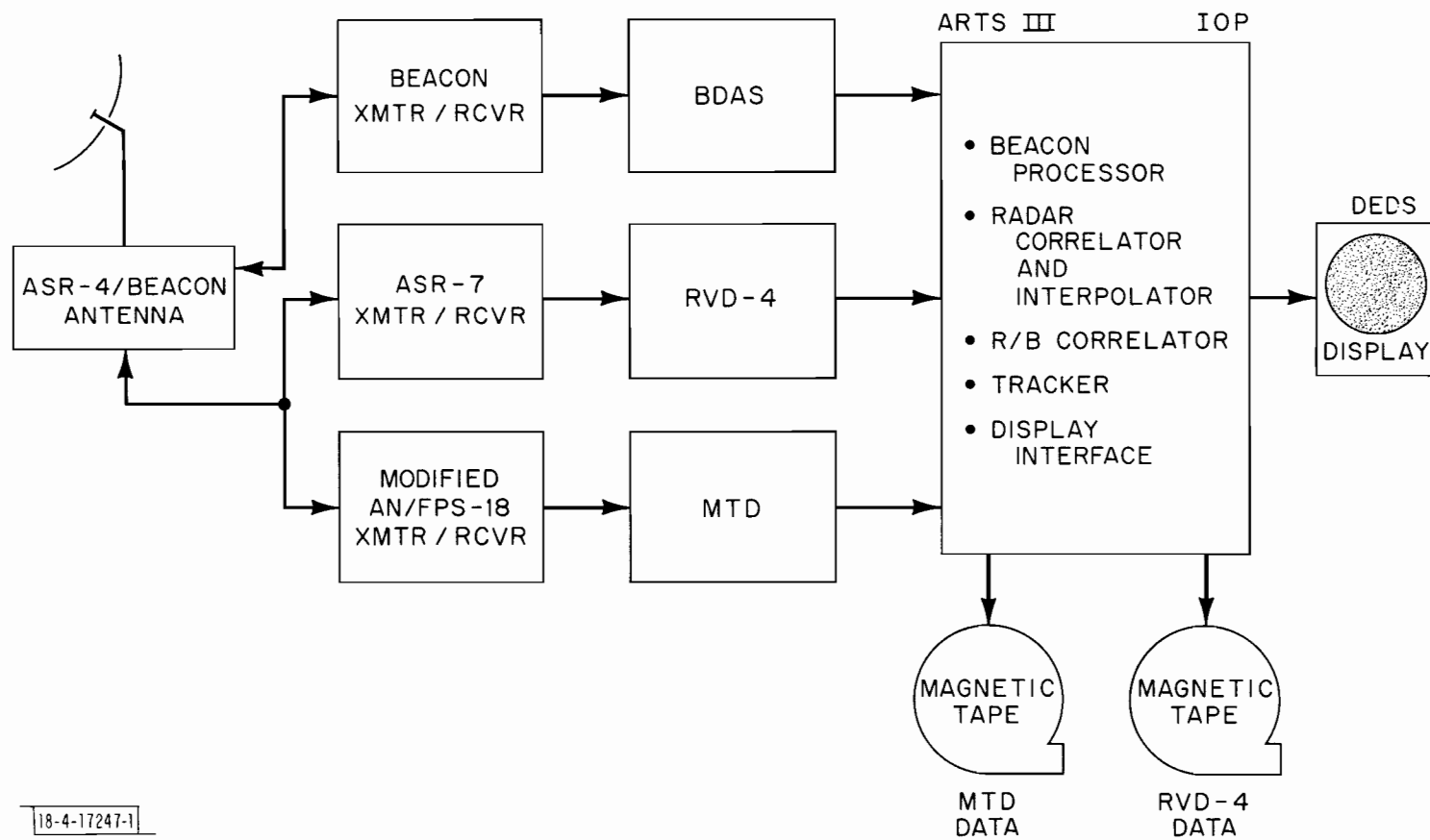


Fig.II-1. MTD/RVD-4 experimental test set-up.

to 0.22 degrees. The MTD and RVD-4 had range accuracies of .022 nmi and .030 nmi respectively. It should be noted that the MTD radar report accuracies were essentially the same as those of the ATCRBS beacon reports. Careful evaluation of the automatic tracking results showed that one reason for superior MTD tracker performance is the accuracy of the reports that it supplies to the tracker. Typical performance of the MTD and RVD-4 in clear regions is shown in Figure II-2.

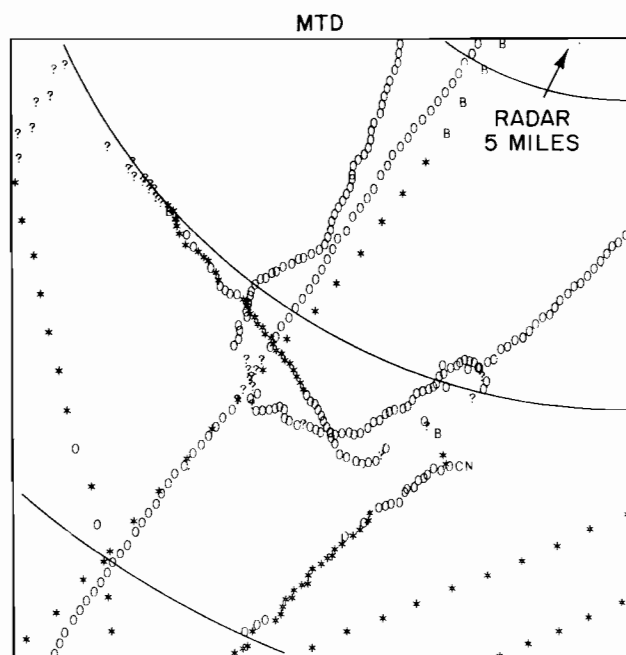
C. Performance in Ground Clutter

On 12 August 1975 a single-engine Piper Cherokee aircraft was flown back and forth over a patch of ground clutter at an altitude of 1000 ft near NAFEC. The ground clutter consisted of distributed clutter and many large discrete scatterers (large buildings). Data from the two-hour (1200 scan) flight was examined in detail. The blip-scan ratio of the MTD radar reports was 0.99, and that of the RVD-4 0.82. Usually the RVD-4 detectability dropped significantly as the aircraft entered the area of heavy clutter, while the MTD's detectability remained near unity throughout the test*. A long-exposure photograph of 40 scans of ARTS-III track data is presented in Figure II-3. The dots represent heavy ground clutter, while the O,*,B,?'s are ARTS-III tracker output symbols. During this block of data, a radar-only target of opportunity crossed back and forth over the controlled aircraft. Note that the MTD processed track data is accurate and solid for both tracks, while the RVD-4 track data is full of large gaps and inaccurate. The subclutter visibility of the processor was measured using a coherent test track generator and a fixed clutter return. The subclutter visibility of the ASR-7/ RVD-4 system was 22 dB, and that of the FPS-18/MTD system 42 dB.

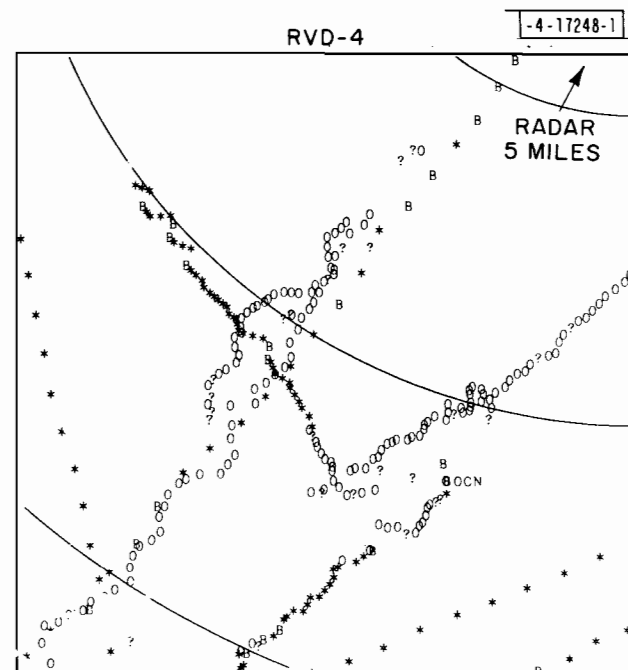
D. Performance in Rain

On 6 August 1975 a small, single-engine aircraft was flown in and out of heavy precipitation for about one hour (700 scans). The MTD radar report data indicated a blip-scan ratio of 0.98, while the RVD-4 radar report data showed a blip-scan ratio of 0.66. The RVD-4 detectability dropped to almost zero

*Some of the RVD-4 loss is due to the tangential aircraft trajectory when the RVD-4 is in the MTI mode.



DISPLAY CODE
 * RADAR/BEACON
 O RADAR ONLY
 B BEACON ONLY
 ? COASTING



LONG EXPOSURE PHOTOGRAPHS OF ABOUT 100 SCANS OF RADAR DATA FROM THE ARTS III TRACKER AT NAFEC WHILE OPERATED WITH DATA FROM THE MTD AND RVD-4 PROCESSORS. THESE DATA WERE TAKEN ON 12 AUGUST 1975. (FIVE MILE RANGE RINGS)

Fig.II-2. MTD/RVD-4, performance compared in 'clear' environment.

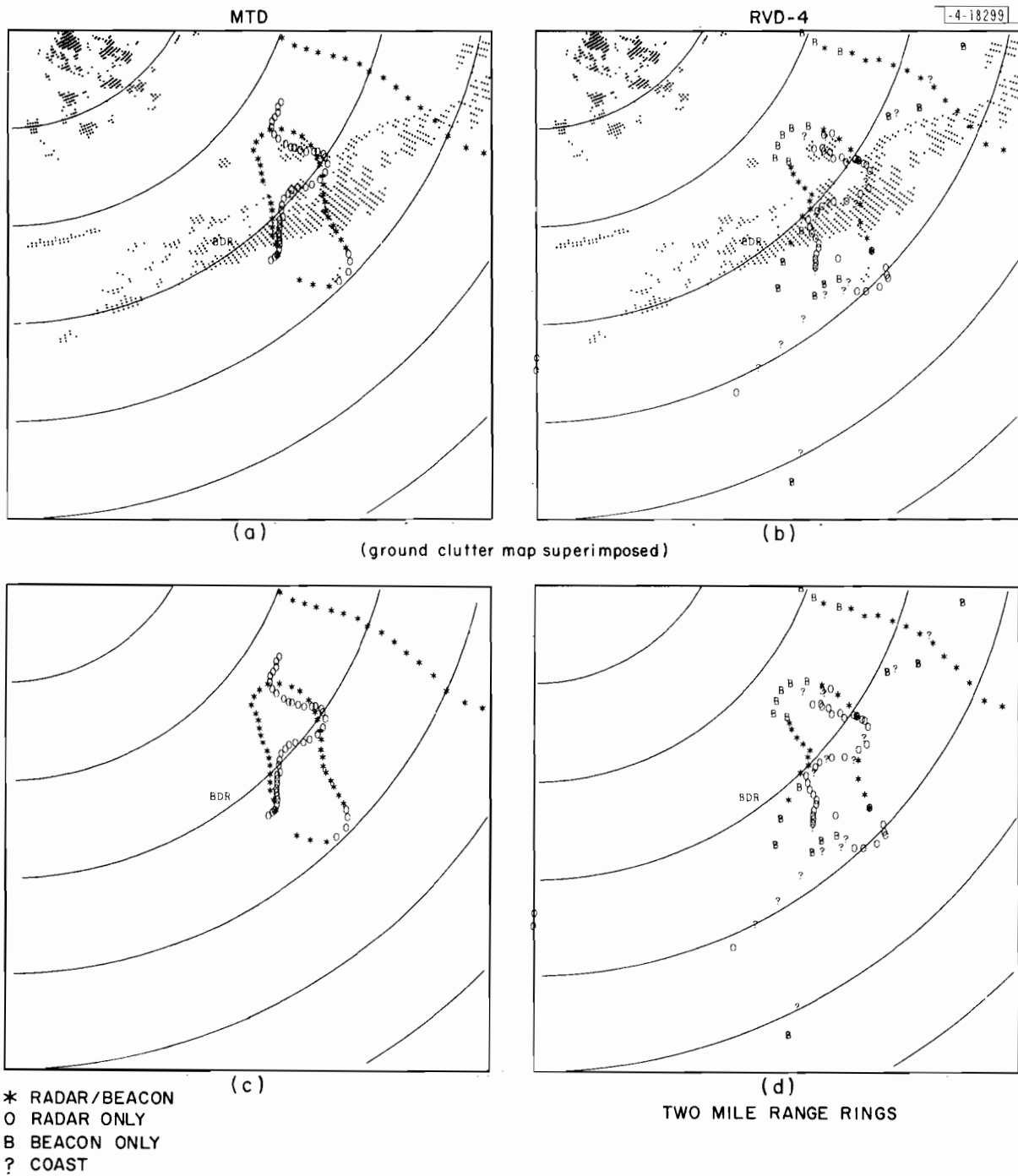
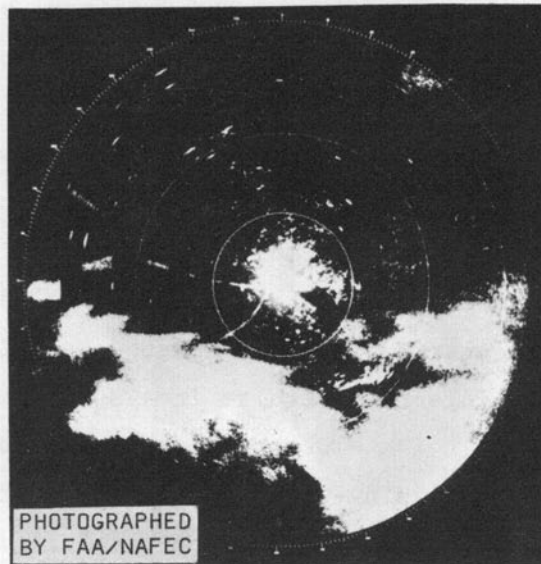


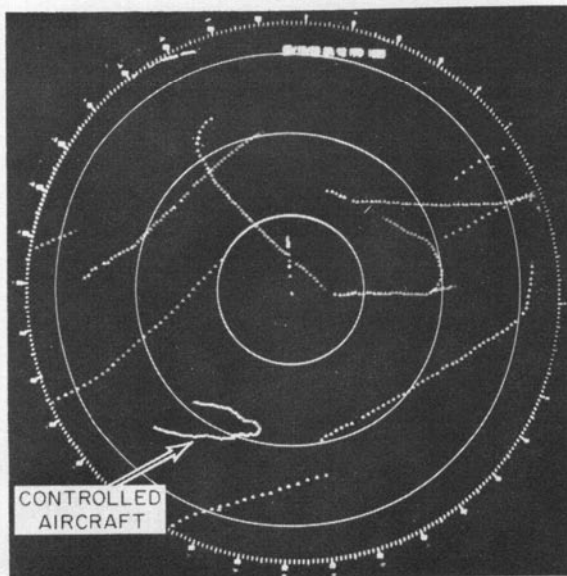
Fig.II-3(a-d). MTD/RVD-4, performance compared in ground clutter.

NORMAL VIDEO

-4-18058



MTD



RVD-4



Fig.II-4. MTD/RVD-4, performance compared in rain clutter.

when the aircraft entered areas of heavy rain, while the MTD maintained a detectability of almost unity. Again, the MTD tracks were more accurate than the RVD-4 tracks. In Figure II-4, 40 scans of radar-only tracker output data from the MTD and RVD-4 are presented along with the Normal Video of the radar to illustrate the performance of both systems. The heavy rain clutter was about 40 dB above the radar receiver noise level. Even in the presence of this heavy rain, the MTD detected the controlled aircraft almost every scan of the radar while maintaining excellent false-alarm performance. (The false alarm rate of the MTD is less than 100 false alarms per scan, and the rate is independent of environmental conditions. This rate results in a negligible false track rate out of the ARTS-III tracker.) The MTD entirely eliminated the false-alarm-in-weather problem common to sliding-window detectors such as the RVD-4. The MTD circumvents the weather problem by coherent doppler filtering so as to achieve sub-weather visibility on aircraft, estimating weather thresholds by averaging over statistically independent, uncorrelated samples.

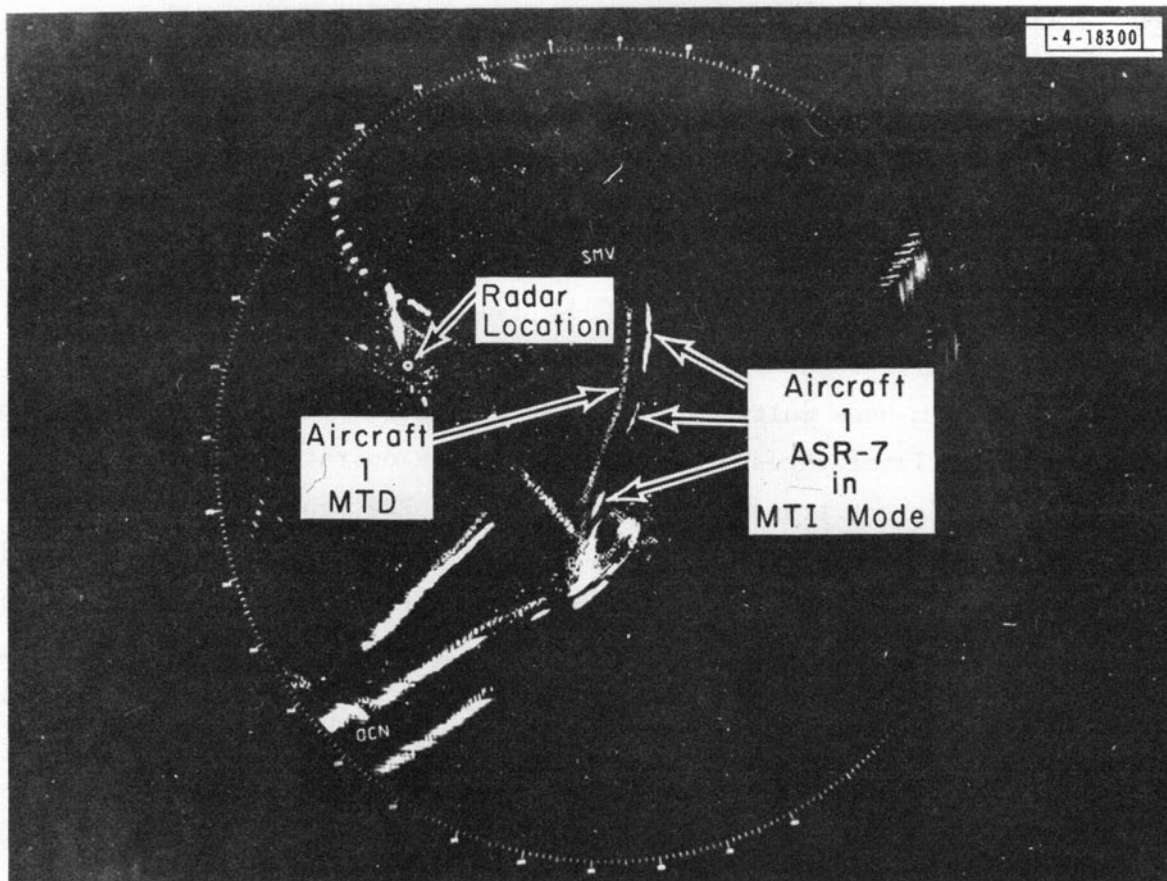
It should be noted that linear polarization was used throughout these tests.

E. Tangential Aircraft Detection Performance

The ability of the sensor/processor systems employing the MTD and RVD-4 to detect aircraft flying tangentially with respect to the radar was measured implicitly in each of the test flights whenever the controlled aircraft turned broadside to the radar. Few detections were lost by the MTD when the aircraft were flying tangentially, but the RVD-4 dropped many tracks because the aircraft's low radial velocity passed into the wide 3-pulse notch used by the RVD-4 when it is in the MTI mode. Figure II-5 illustrates how the fine grained clutter map permitted detection of aircraft flying tangentially over the clutter.

F. Conclusions

While both processors exhibited adequate detection and false-alarm performance in the clear, the detection and false alarm performance of the MTD was far superior to that of the RVD-4 in rain and ground clutter. MTD processed radar reports were significantly more accurate than RVD-4 radar reports, and the MTD did not suffer from track dropouts while tracking tangentially flying aircraft, as did the RVD-4.



THIS LONG EXPOSURE PHOTOGRAPH SHOWS THE RELATIVE PERFORMANCE OF THE FPS-18/MTD SYSTEM AND THE ASR-7 IN THE MTI MODE. THE TWO RADARS ARE CO-LOCATED IN THE UPPER LEFT PORTION OF THE DISPLAY. THE OUTPUT OF THE TWO RADARS IS SLIGHTLY OFFSET ON THE PPI TO FACILITATE EXAMINATION OF THE TRACKS. THE MTD PROCESSOR CLEARLY DETECTS THE TANGENTIALLY FLYING AIRCRAFT (MARKED 1), WHILE THE TRACK FROM THE ASR-7 IN THE MTI MODE CONTAINS LONG GAPS WHEN THE AIRCRAFT IS IN THE ZERO RADIAL VELOCITY NOTCH OF THE MTI CIRCUIT. SINCE THE RVD OPERATES ON THE MTI VIDEO DATA IT CANNOT PERFORM BETTER THAN THE DATA PROVIDED TO IT BY RADAR.

Fig.II-5. MTD/RVD-4, performance compared for tangential (zero radial velocity) aircraft.

III. DESCRIPTION OF THE MTD AND THE RVD-4

A. Moving Target Detector^{*}

The Moving Target Detector is a digital signal processor employing linear, wide dynamic range, coherent doppler filtering and adaptive thresholding techniques. See Figure III-1. In addition, it contains a fine grained ground clutter map in which ground clutter thresholds are stored and continuously updated. Each of the ASR's 360,000 range-azimuth cells is processed into 8 near optimum doppler filters and each of the approximately 2,900,000 range-azimuth - doppler cells is adaptively thresholded every scan of the radar. The FPS-18/MTD system uses multiple PRF's for elimination of blind speeds, and when used with mean level thresholding provides CFAR operation in heavy weather. When used with a coherent transmitter, the multiple PRF scheme provides rejection of second-time-around-clutter. The doppler filters used are close approximations to the so-called optimum processor. These filters are generated by sequentially processing groups of 10 pulses through a three pulse MTI canceller, an 8 point FFT, and frequency domain weighting to reduce doppler sidelobes. This combination gives MTI improvement factors which are about 100-fold better than conventional non-linear MTI processors and which is within about 2 dB of the optimum possible.

The MTD processor is implemented as a hard-wired, pipeline, digital processor (see Figure III-2) with capability to process the full 360 degree coverage of an ASR out to 48.nmi. The MTD was constructed from standard TTL integrated circuits except for the input data core memory, the memory used to buffer the ground clutter map data from the processor to the disc memory, and the disc memory.

In addition to the input core memory and the clutter map disc memory, the MTD consists of approximately 900 TTL integrated circuits. The MTD includes all of the digital timing for the radar and generates 31 MHz, 0.8 μ sec pulses which are up-converted to S-band (in the transmitter) to become the transmitted pulses.

^{*}The MTD is described in detail in References 1 through 6.

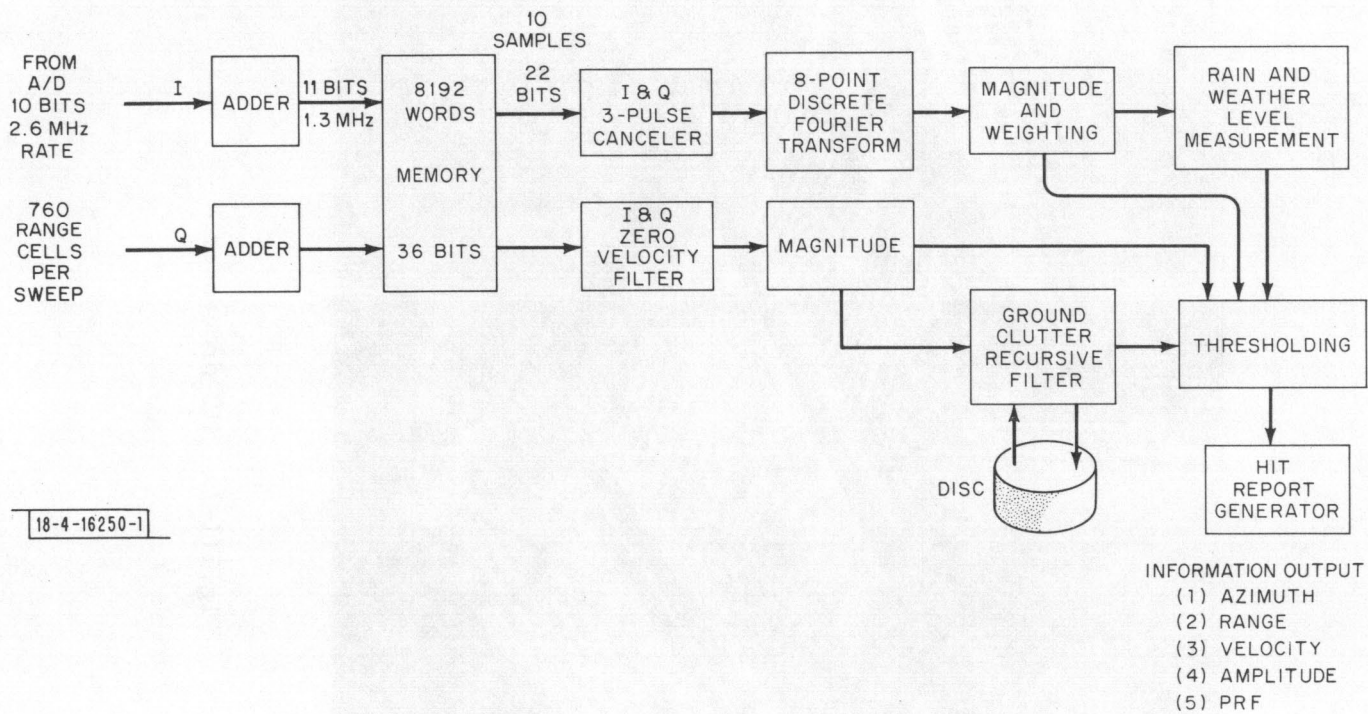


Fig.III-1. MTD processor block diagram.

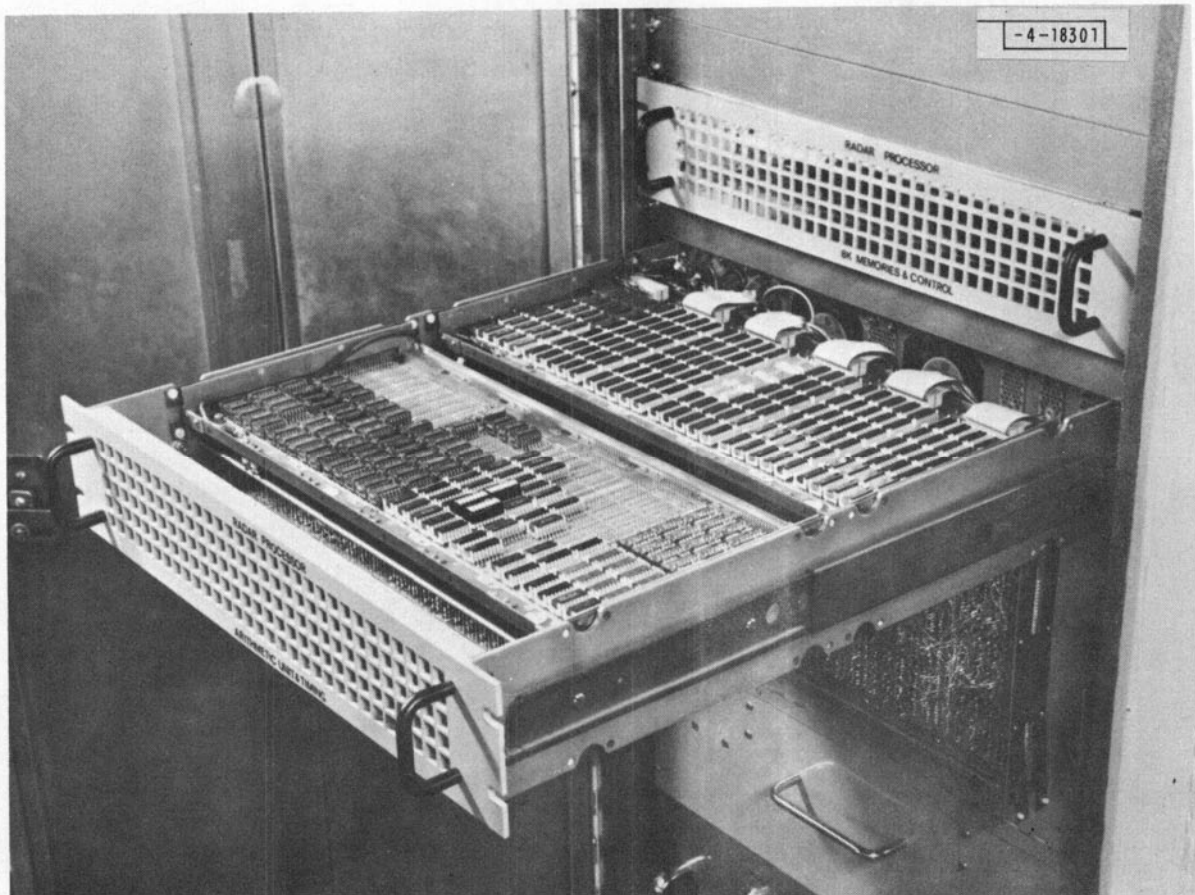


Fig.III-2. MTD processor.

B. Radar Video Digitizer (RVD-4)

The RVD-4 is a good example of a modern adaptive non-coherent sliding-window detector system. Both log-normal and MTI video signals are generated in the radar. The RVD-4 adaptively chooses log-normal or MTI video signals for coverage sectors measuring about 2 nmi by 2.8 degrees. The choice is made depending upon whether or not ground clutter, weather clutter or receiver noise are sensed in each sector.

Sliding window detection is a double thresholding detection technique. The first threshold, a rank order quantizer, converts the video signals into zeros or ones. The second threshold, a sliding window detector, declares the presence or absence of an aircraft. This is a form of non-coherent integration. Previous sliding window detection schemes have used fixed values for the leading and trailing edge values of the sliding window detector. Recently, however, it has become apparent that the false-alarm-in-rain problem may be alleviated by making the leading edge threshold value of the sliding window detector dependent on whether the clutter is correlated or not (Ref. 8). The RVD-4 differs from its predecessor (the RVD-3) in that it measures the degree of correlation of the clutter signals over the 2 nmi by 2.8 degree sector and uses this information to adaptively set the sliding window threshold for constant false alarm rate operation. When used with the RVD-4, the ASR employs a staggered PRF to eliminate blind speeds. A complete description of the RVD-4 is given in Reference 7.

IV. EXPERIMENTAL SETUP AT NAFEC

The MTD was integrated into an existing experimental facility, the Terminal Facility for Automated Surveillance Testing (TFAST), at NAFEC. This facility is used by the FAA for testing various aspects of the augmented ARTS-III system and other radar developments. The facility was reconfigured so that the MTD could be operated either alone or simultaneously with the RVD-4. When operated alone the MTD could process i-f signals from the ASR-5, ASR-7, or FPS-18 located at the site. When the MTD and the RVD-4 were operated simultaneously, it was necessary for the MTD to operate with the FPS-18, and the RVD-4 to process video from the ASR-5 or ASR-7. However, the radar antenna is only available to the ASR-5 when the FPS-18/ASR-7 complex is connected to the dummy load and vice versa. The normal mode of operation for the MTD is in conjunction with the modified FPS-18. Further details of the experimental setup are given in Reference 1.

In order to analyze MTD and RVD-4 test data, output track position data as well as other data was output to magnetic tape for later analysis. MTD, RVD-4, and beacon threshold crossings, including timing and scan number information were recorded and this bulk data was then processed through the ARTS-III tracker. It should be noted that the MTD and RVD-4 data were processed by the same radar-beacon correlator and the same ARTS-III tracker.

Track data was recorded and used to determine the performance of the radar, MTD, RVD-4, and ARTS-III tracker processed data. Radar, beacon and track information was extracted for subsequent data reduction and analysis.

V. DETAILS OF SPECIFIC TESTS

A. Detection Performance in Thermal Noise

The probability of detection vs signal-to-noise ratio for the FPS-18/MTD and the ASR-7/RVD-4 systems was measured in the presence of thermal noise. The targets used for the measurement were generated by a coherent test target generator simulating 96 antenna scan modulated targets per scan. Thirty-two targets are in each of three concentric rings. The targets are moved in range and azimuth to average effects of range and azimuth straddling. The FPS-18/MTD and ASR-7/RVD-4 systems were adjusted so that the average power divided by the receiver noise figure was the same for both systems. Under these conditions* the probability of detection of a test target per scan was measured as a function of the signal to noise ratio. This was done at a probability of false alarm of 10^{-5} for each system. A complete description of the measurement techniques used is given in Reference 1. Figure V-1 depicts the results of these measurements. It is evident that both systems have essentially the same detection capability in thermal noise.

B. Comparative Test Flights - General

1. Objectives

The basic objective of the MTD/RVD-4 tests was to determine which processor would perform better as an element in a primary radar sensor for automated terminal radar air traffic control. Accordingly, the objective of the flight tests was to measure the relative effectiveness of the MTD and RVD-4 in such a sensor. It was decided that the most effective way to do this would be to make a direct comparison between the MTD operated with a modified FPS-18** and a radar digitizer system, the RVD-4 operated with an ASR-7 radar.

* After these measurements were made it was discovered that the IF filter used at NAFEC in the FPS-18 has been designed with a bandwidth of 2.6 MHz at the 1 dB points rather than the 3 dB points as had been assumed. This discrepancy caused the actual noise bandwidth of the FPS-18/MTD system to be about 1.5 dB greater than was anticipated.

** The FPS-18 was used because a coherent transmitter was desired and ASR-8's were not available at the time of the MTD test and evaluation.

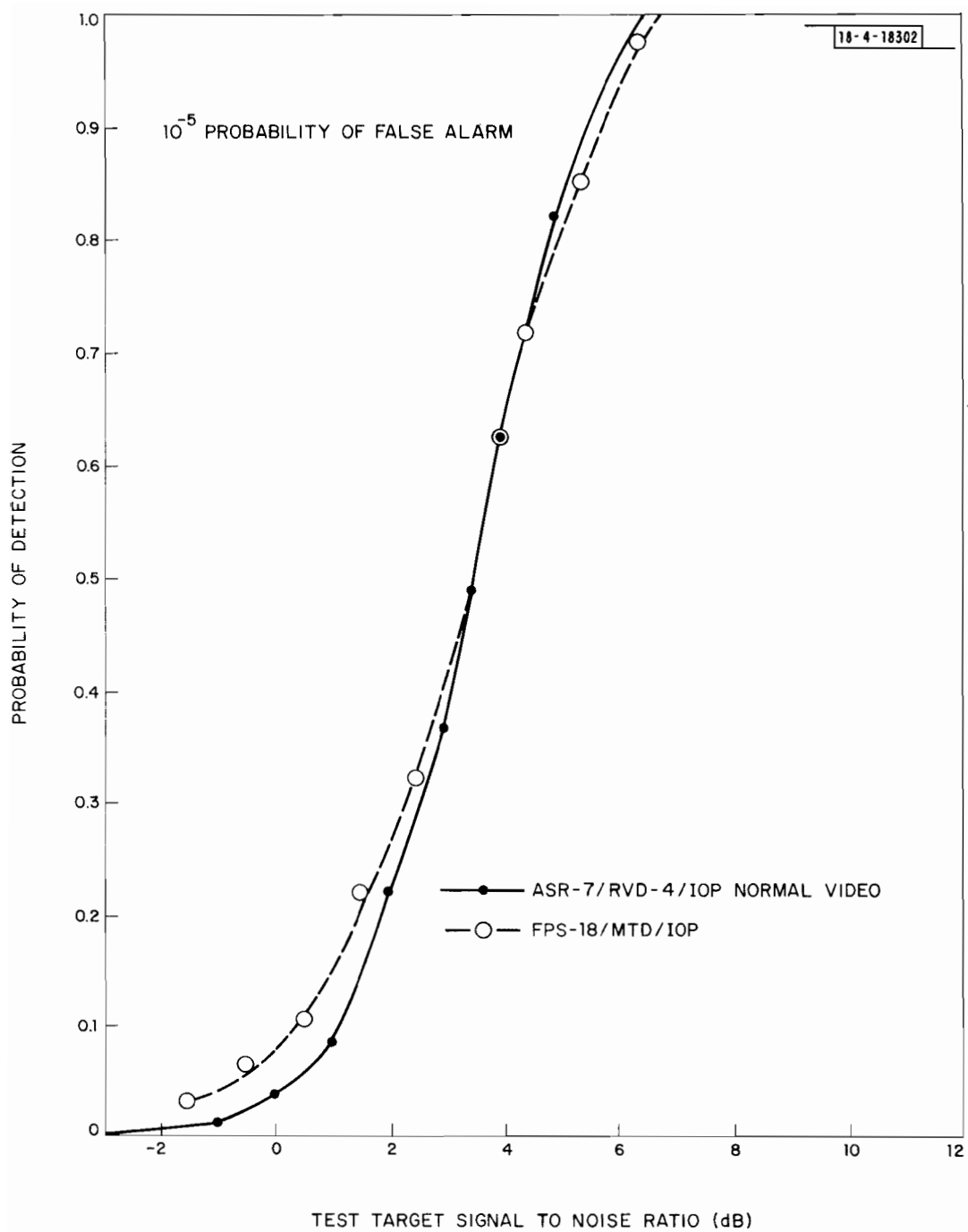


Fig.V-1. MTD/RVD-4, probability of detection in thermal noise.

The absolute detection sensitivity in receiver noise obtainable from a given radar transmitter-receiver was not an issue in these flight tests. The primary basis for comparison between the two processors was their relative performance in detecting and reporting the position of aircraft whose echoes are competing with clutter returns from any source (ground, weather, birds, etc).

Also, since several recent mid-air collisions have involved at least one small aircraft not equipped with an ATCRBS transponder, another objective was the evaluation of the processor's effectiveness in improving detection of small aircraft. Such general aviation aircraft fly at relatively low airspeeds.

2. Normalization

Ideally, the flight testing should have been done with the MTD and the RVD-4 processors receiving information from the same radar. This approach was considered initially but rejected because the radar pulse repetition rates required by the processors are different. Major redesign of at least one of the processors would have been required to make single radar tests practical. The approach chosen was to operate the two radar-processors through a common antenna (by means of a diplexer), so that they could be operated simultaneously while the test aircraft was flying.

The results of the simultaneous flight tests made in this manner would have been easier to interpret if the two radars were identical. However, since the radars were not identical, their performance was normalized: the quotient of average power divided by system noise figure for each of the radars was adjusted to be the same.

The difference in carrier frequency of the two radars necessitated by the diplexer remains as a potential source of error in the comparison of the two systems. Radar frequency can affect target cross section, antenna performance and radar propagation.

On a single scan, target scintillation can cause large differences in the amplitude of radar returns at slightly different frequencies. However, when averaged over many scans, differences in aircraft cross section due to small differences in radar frequency are usually negligible.

As a function of frequency, the behavior of ASR radar antennas are a compromise between constant aperture and constant gain. Antennas which are designed for best aperture efficiency tend toward constant aperture, hence gain increases as frequency is increased. On the other hand, antennas which are designed for outstanding sidelobe performance tend toward constant gain, hence increasing frequency causes decreased effective aperture.

Two propagation mechanisms seem important in these flight tests. At shorter ranges and higher altitudes a free space model is appropriate. At lower altitudes or longer ranges the radar propagation is better described by including the interference zone pattern propagation factor in the radar equation.

The MTD was operated in conjunction with the FPS-18 radar at a radar frequency of 2710 MHz. The RVD-4 processed video from an ASR-7 which operated 85 MHz higher in frequency. It can be shown that differences in received signal energy caused by that difference will be limited to less than 1 dB over all combinations of antenna performance and propagating mechanisms considered here.

3. Aircraft

The primary target in all of the flight tests was a Piper Cherokee, a 4-place, low-wing airplane originally introduced as a training plane. It has a 150-horsepower engine and fixed landing gear. Over the years, variations of the basic design with higher horsepower and retractable landing gear have been developed and marketed. In size, speed, and gross weight Cherokees are typical, small, general aviation aircraft. Detailed radar cross section

measurements have been made on a 150-horsepower Cherokee (Reference 9). The specific aircraft used in the MTD flight tests were as follows* :

N-3553 - a Cherokee Arrow with 200 horsepower and retractable landing gear,

N-56639 - a Cherokee Arrow similar to the one above,

N-43403 - a Cherokee Warrior (a later model) with 150 horsepower, fixed landing gear and a somewhat longer wing than earlier Cherokees.

C. Detection and False Alarm Performance in Rain

On 6 August 1975, the aircraft detection performance of the MTD and the RVD-4 were measured in a rain environment. A Piper Cherokee Arrow aircraft was used for this test. The duration of the test was about two hours (1600 scans). The beacon equipped aircraft was vectored through heavy rain clouds during the test while the intensity of the rain was measured on an A-scope. Its intensity varied from 0 to 40 dB above the receiver noise level. The normal video of the radar is presented in Fig. V-2 to show the location of the storm. Data from the test was collected on magnetic tape for later analysis. Thirty scan blip-scan ratios of the radar reports after the correlator/interpolator for both the MTD and RVD-4 processed data were measured using the interactive displays. Fig. V-3 plots the results. (The gaps in the data were due to the time required to rewind and change tapes). The sharp dips in the detectability of the aircraft during the first hour were caused by inadvertently vectoring the aircraft out of the radars elevation coverage. The location of the aircraft during these periods was at a range of greater than 20 miles and an altitude of less than 1500 ft. During significant portions of the last hour of the test, the test aircraft flew through rain clouds whose backscatter intensity was 30 to 40 dB above receiver noise. As in Fig. V-3, the detection performance of the MTD in these heavy rain clouds

*The aircraft used in the flight tests are not the same model as the one measured in the RATSCAT tests (Reference 9). However, they are all similar and there is no reason to suspect that the radar cross section of these airplanes is significantly larger than that reported in that reference. There is, conversely, reason to suspect that the Arrows with landing gear retracted present somewhat smaller radar cross section for at least some aspect angles.

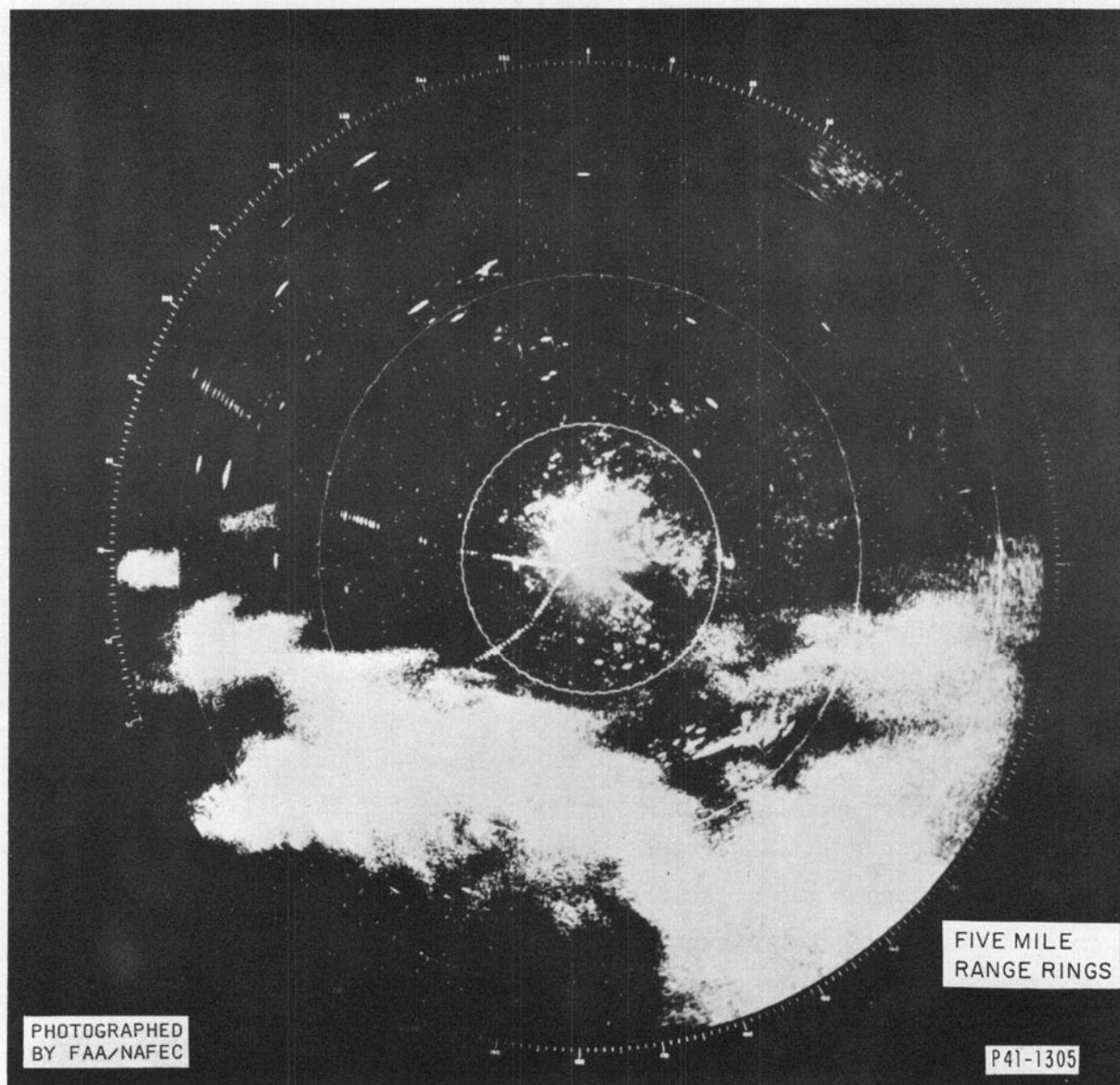


Fig.V-2. Normal video of rain (6 August 1975); 5 nmi range rings.

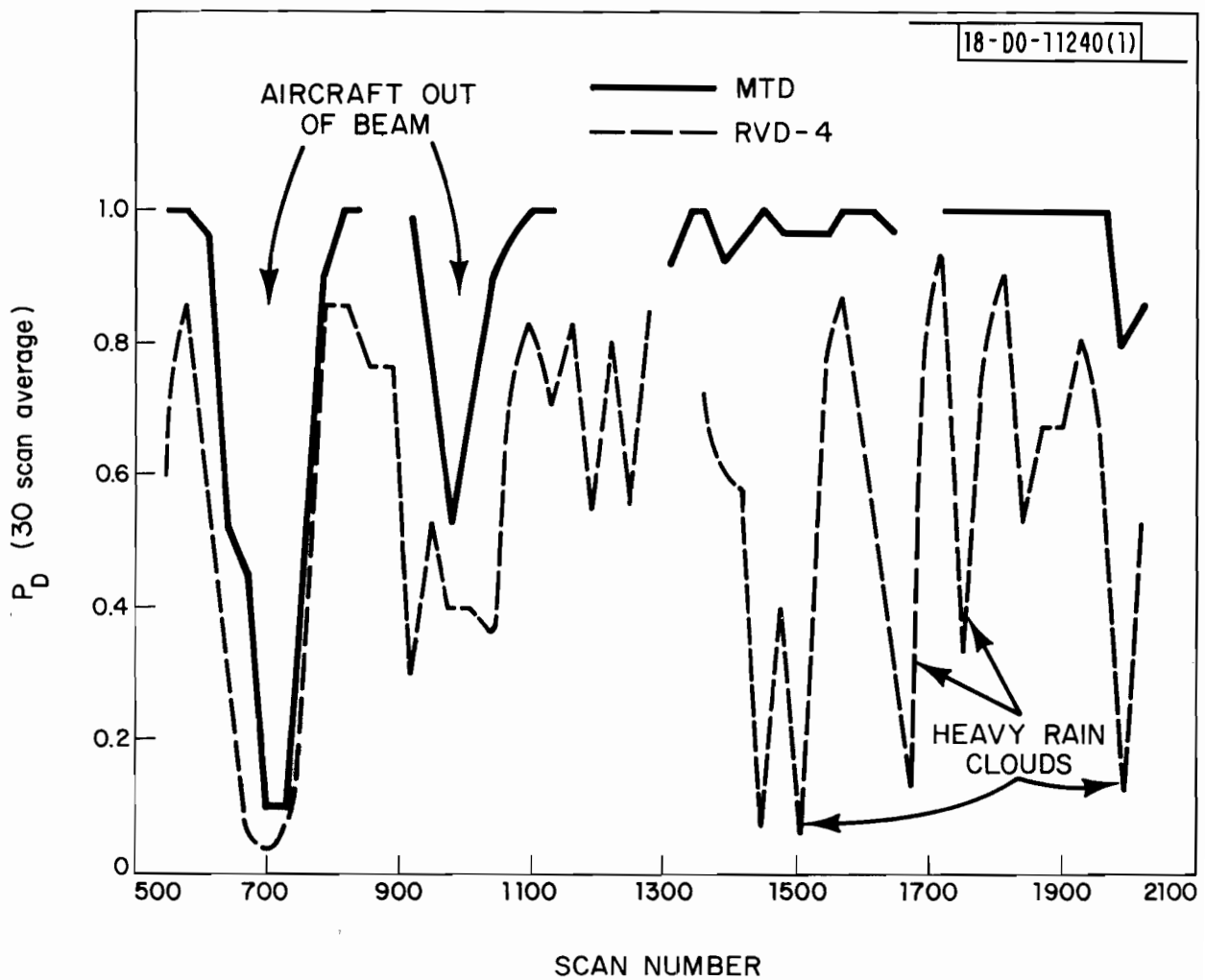
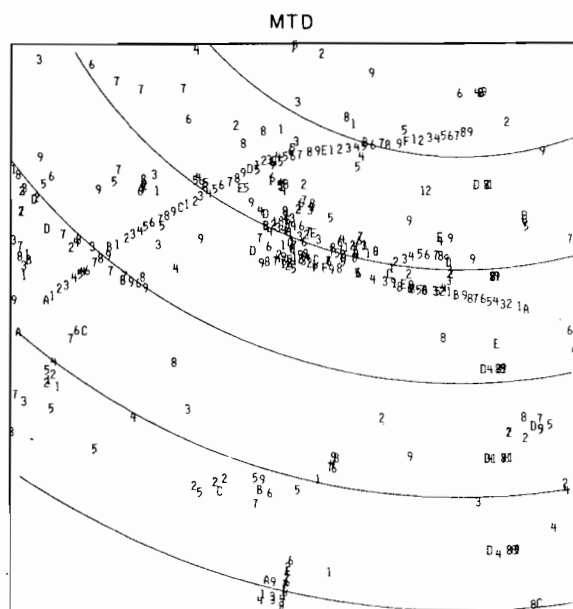


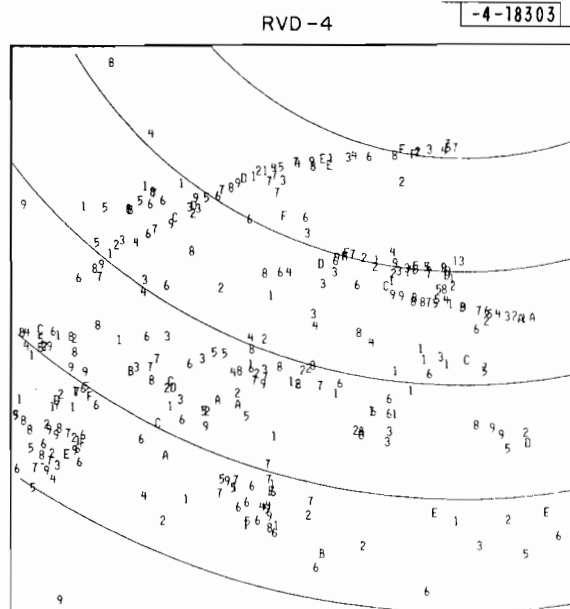
Fig.V-3. Blip/scan ratio during rain (6 August 1975).

was excellent, while the detection performance of the RVD-4 was poor. The sharp dips in detectability of the RVD-4 correlate well with times when the test aircraft entered areas of heavy rain. For the portion of the test flight when the aircraft was within the radars elevation beam the MTD reports had an average measured blip-scan ratio of 0.98 while the RVD-4 processed data had an average measured blip-scan ratio of 0.66. The RVD-4 missed detections were highly correlated and caused the ARTS-III tracker to drop track often for many scans.

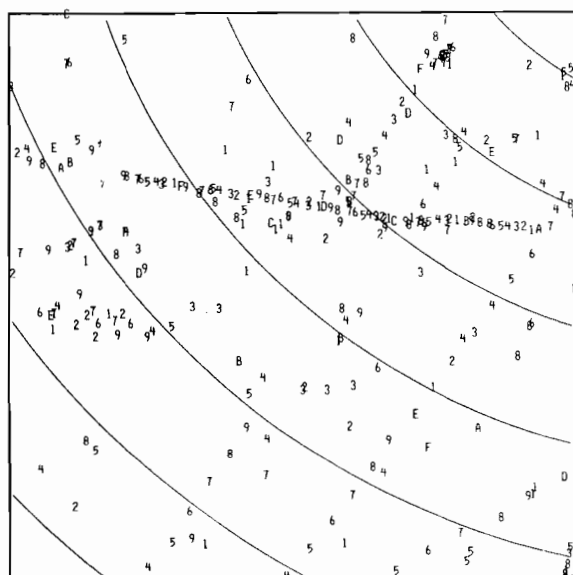
In Figures V-4 through V-15, the radar reports and ARTS-III radar-plus-beacon tracker output is presented for both the MTD and RVD-4 processed data (scans 1370 to 2020). These scans correspond to periods when the test aircraft was flying through heavy rain clouds (30-40 dB clutter to noise ratio). Note that during these periods the MTD had a blip-scan ratio close to unity whereas the RVD-4 processed data had a blip-scan ratio of less than 0.50. To obtain the tracking performance of the MTD data without beacon assistance, the recorded data was played back through the ARTS-III tracker with the beacon data inhibited. The MTD and RVD-4 radar-only tracker output is presented in Figs. V-16 through V-19. The MTD and RVD-4 data for a 40 scan segment of data in the north west portion of the radar's coverage is displayed in Fig. V-20 to indicate the relative false alarm performance of the MTD and RVD-4 radar report and track data. There are many false alarms and false tracks in the case of the RVD-4, whereas in the case of the MTD processed data the false alarms are controlled and virtually no false tracks occur. In addition, the MTD maintains excellent detection performance on all aircraft. Figure V-21 shows the automated tracker output for the MTD and RVD-4 data in Fig. V-20 reprocessed through the ARTS-III tracker with the beacon data inhibited. Again the MTD tracks approach unity blip scan ratio with zero false tracks. Finally in Fig. V-22 long exposure photographs depict the MTD and RVD-4 ARTS-III radar-only tracker output taken during the detection in precipitation test of 6 August 1975. The normal video of the radar is presented along with the ARTS-III output in order to show the location of the heavy rain.



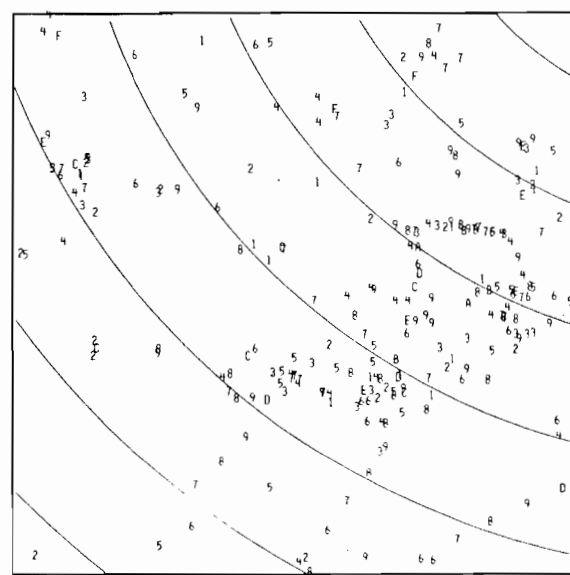
SCANS 1370-1429



SCANS 1370-1429



SCANS 1430-1489



SCANS 1430-1489

Fig.V-4. MTD vs RVD-4, radar reports in rain. (Scans 1370-1429 and 1430-1489, 6 August 1975).

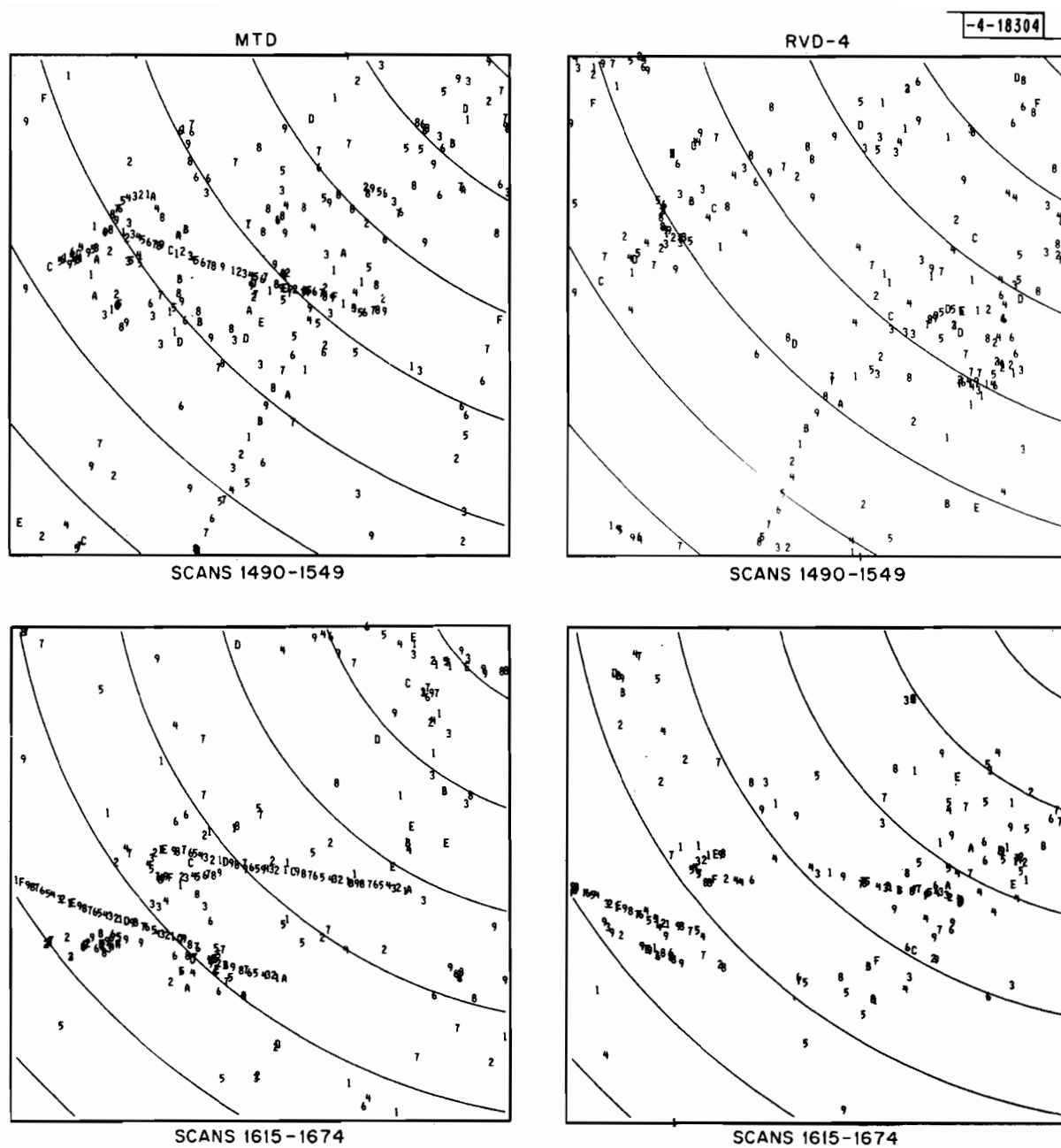
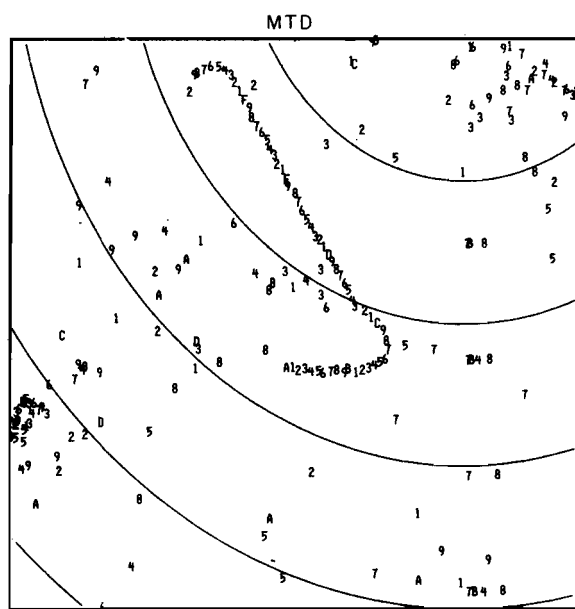
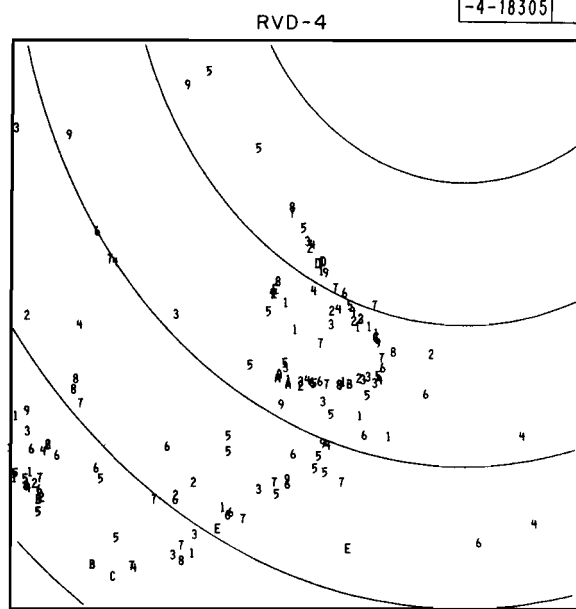


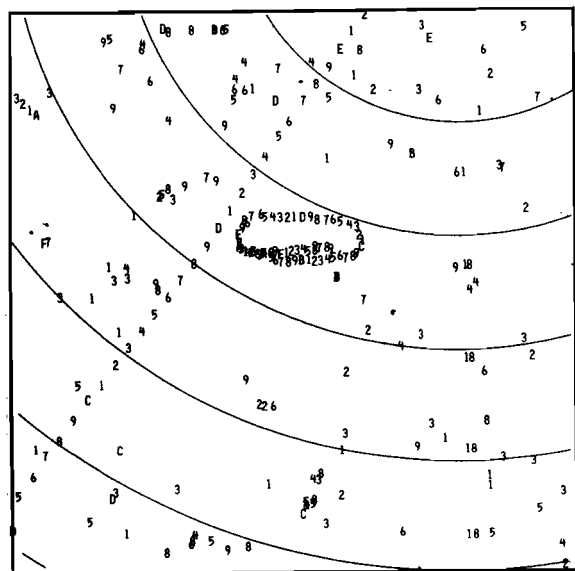
Fig.V-5. MTD vs RVD-4, radar reports in rain. (Scans 1490-1549 and 1615-1674, 6 August 1975).



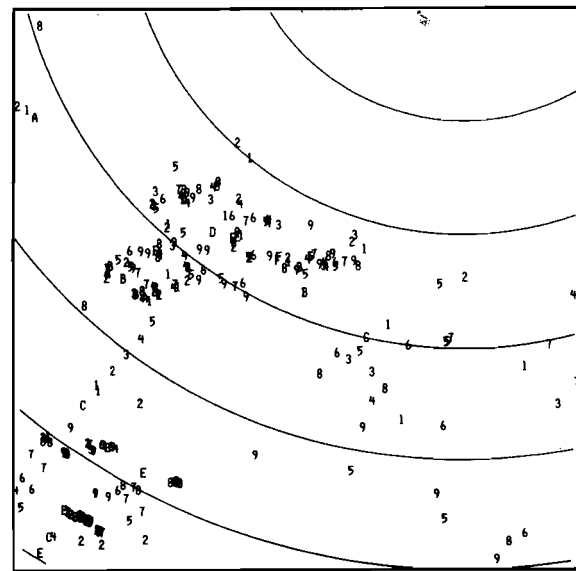
SCANS 1720-1779



SCANS 1720-1779



SCANS 1840-1899



SCANS 1840-1899

Fig.V-6. MTD vs RVD-4, radar reports in rain. (Scans 1720-1779 and 1840-1899, 6 August 1975).

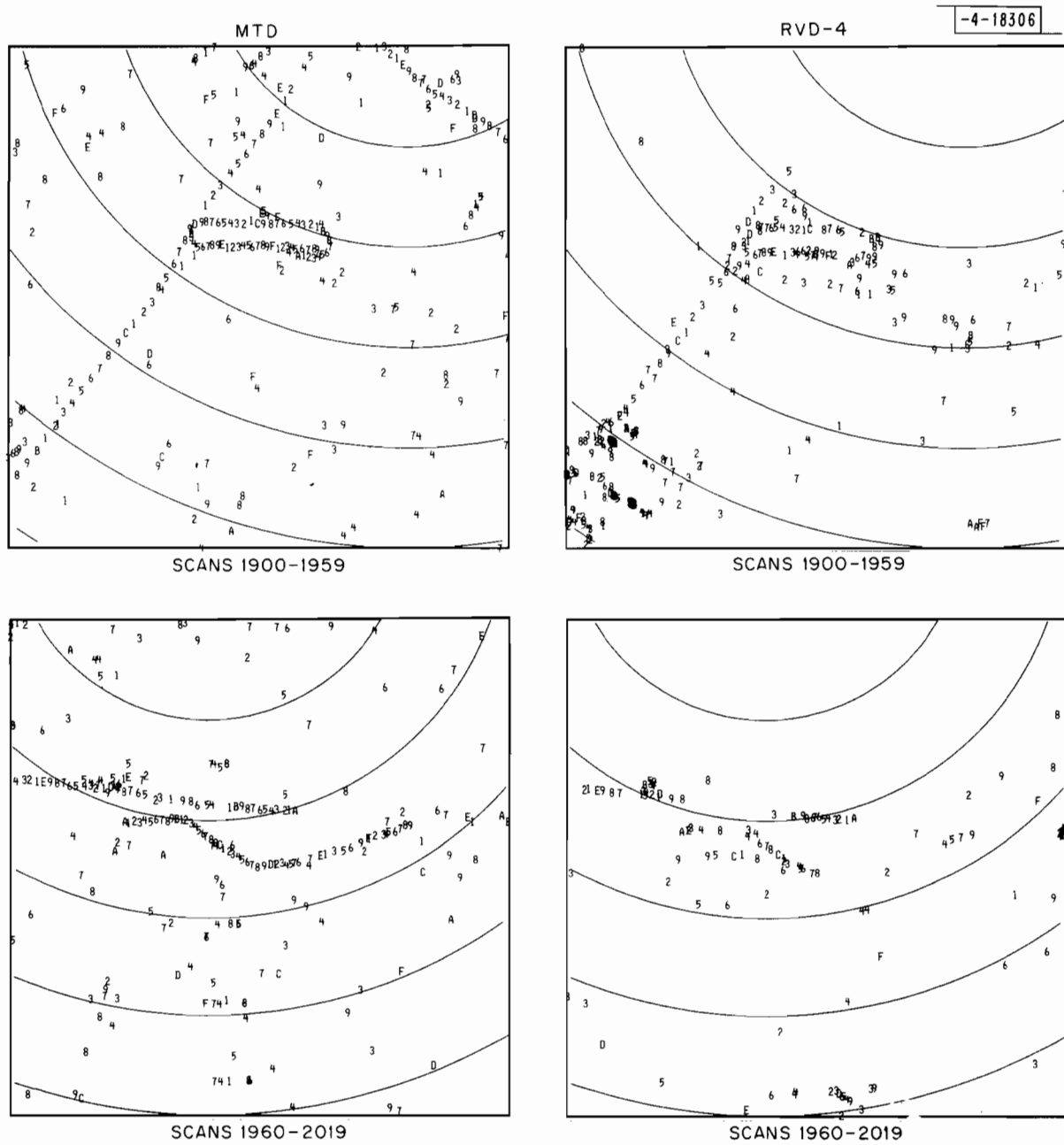


Fig.V-7. MTD vs RVD-4, radar reports in rain. (Scans 1900-1959 and 1960-2019, 6 August 1975).

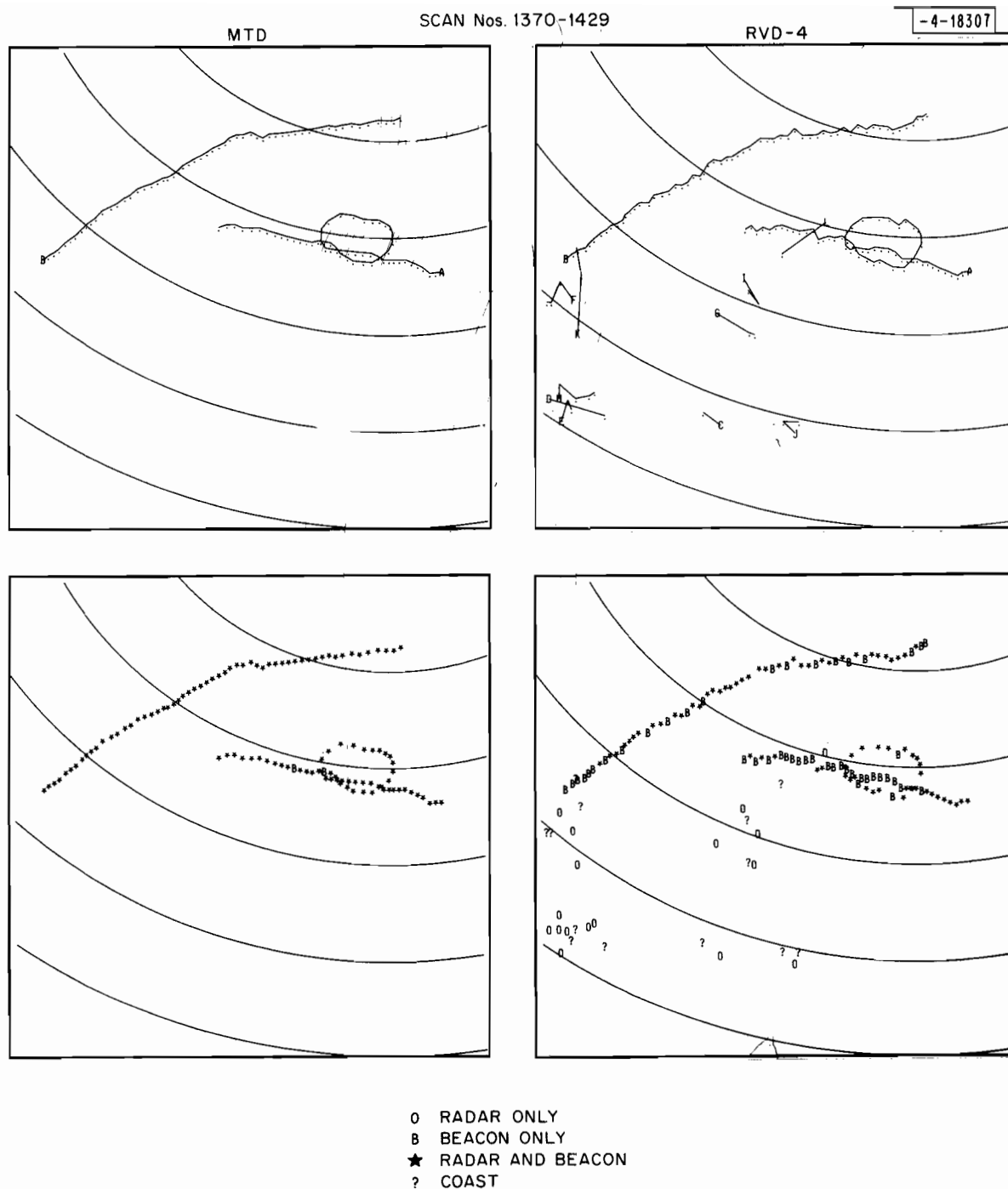


Fig.V-8. MTD vs RVD-4, ARTS-III tracker output in rain.
 (Scans 1370-1429, 6 August 1975).

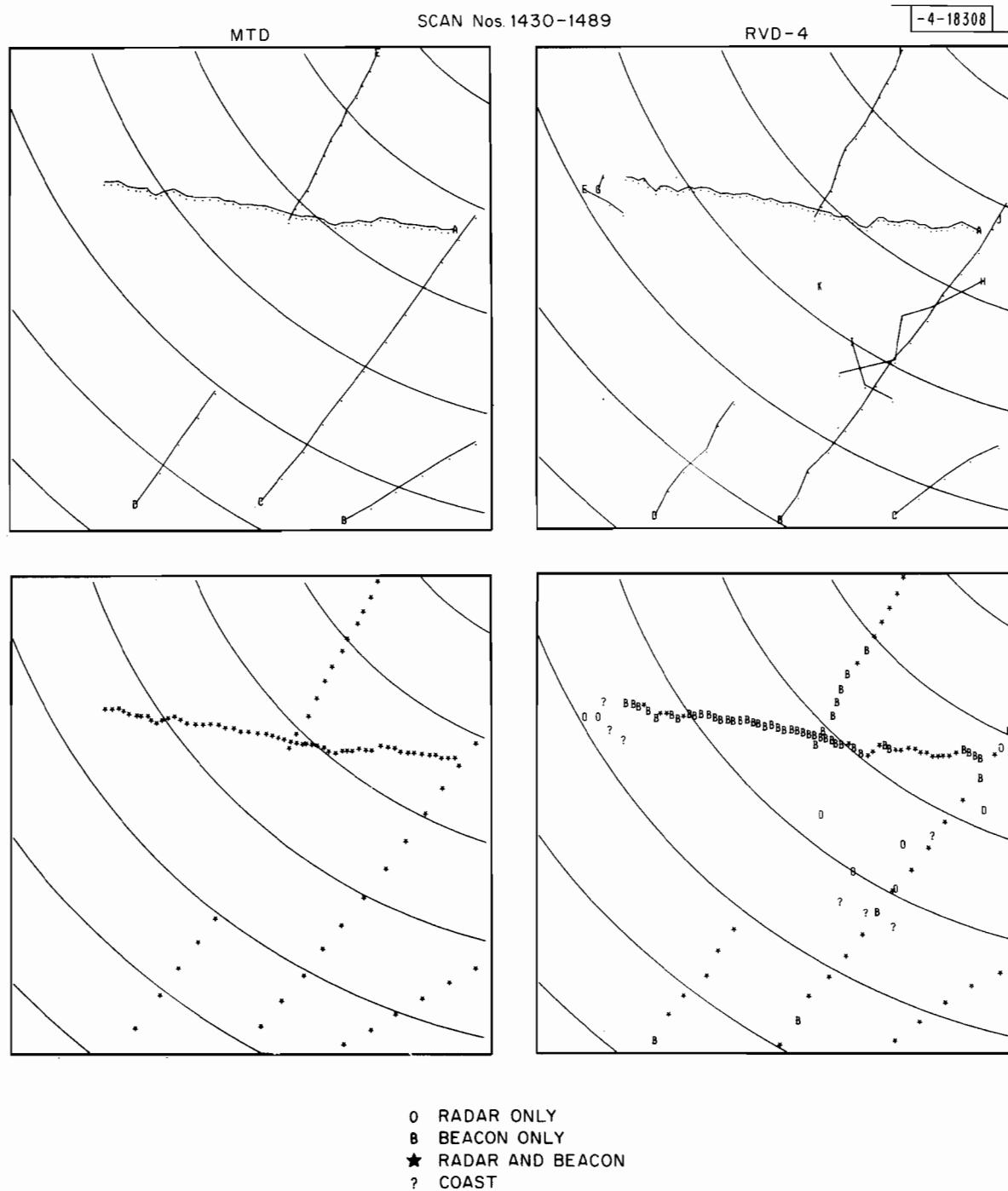


Fig.V-9. MTD vs RVD-4, ARTS-III tracker output in rain.
 (Scans 1430-1489, 6 August 1975).

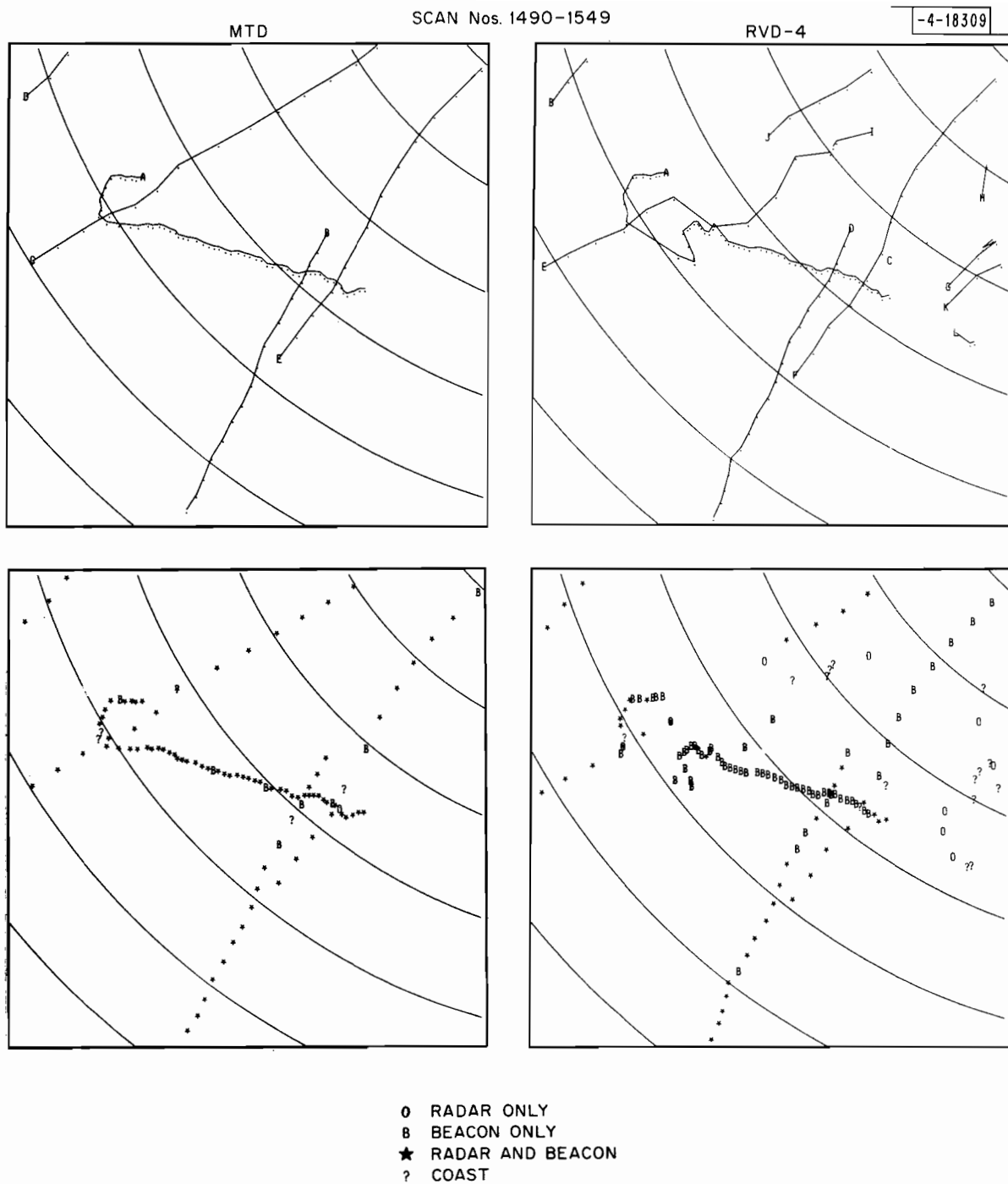


Fig.V-10. MTD vs RVD-4, ARTS-III tracker output in rain.
 (Scans 1490-1549, 6 August 1975).

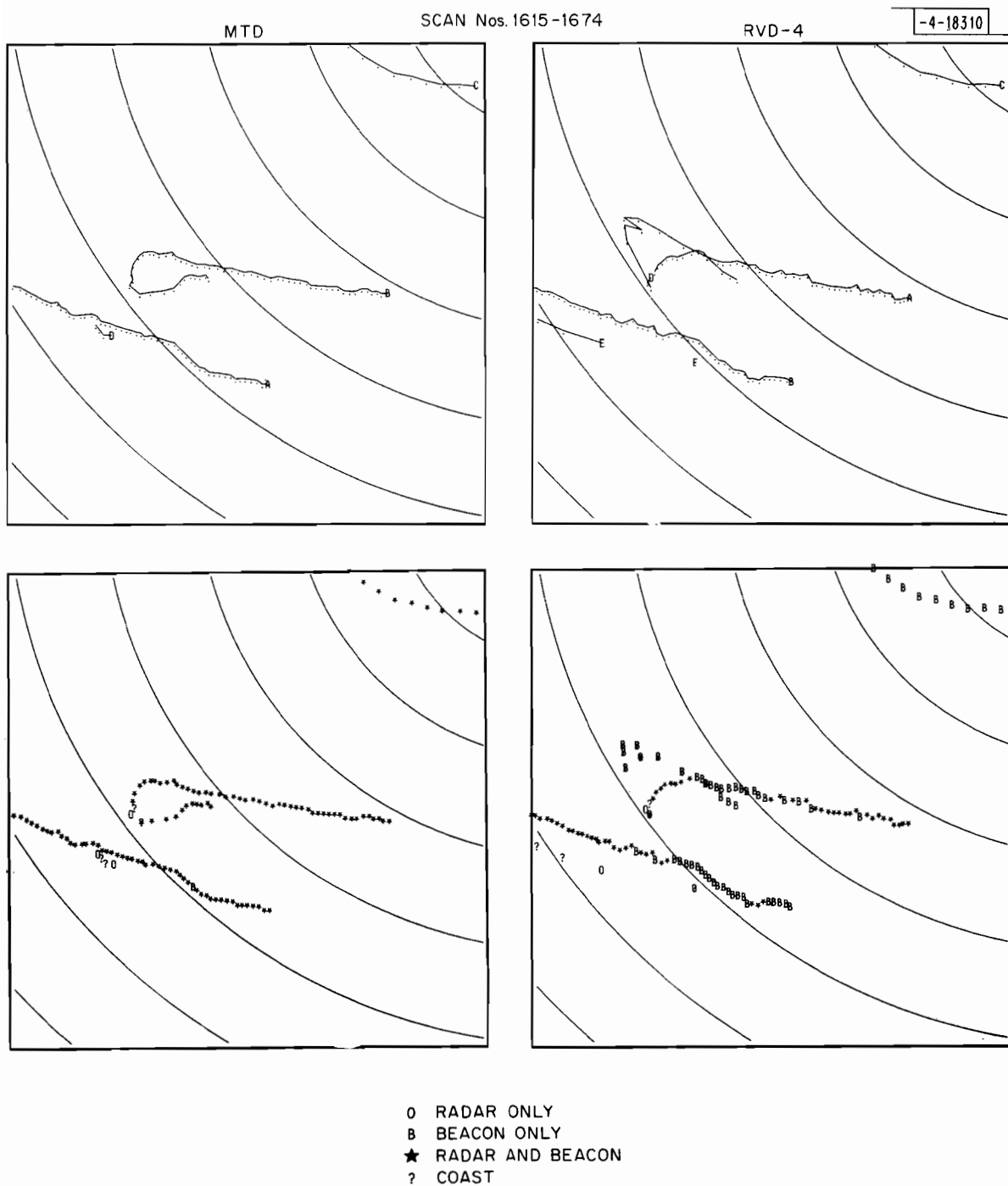


Fig.V-11. MTD vs RVD-4, ARTS-III tracker output in rain.
(Scans 1615-1674, 6 August 1975).

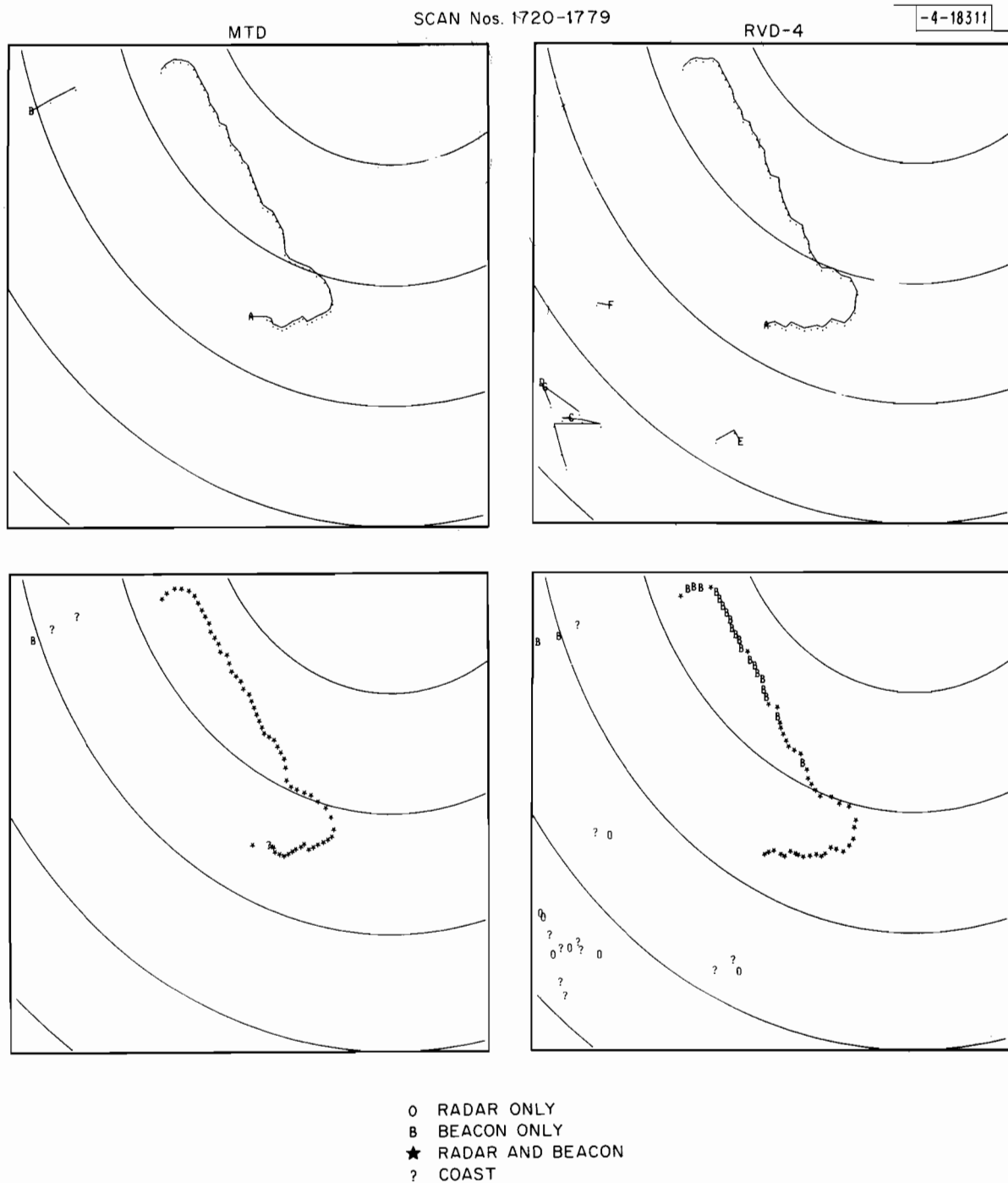


Fig.V-12. MTD vs RVD-4, ARTS-III tracker output in rain.
(Scans 1720-1779, 6 August 1975).

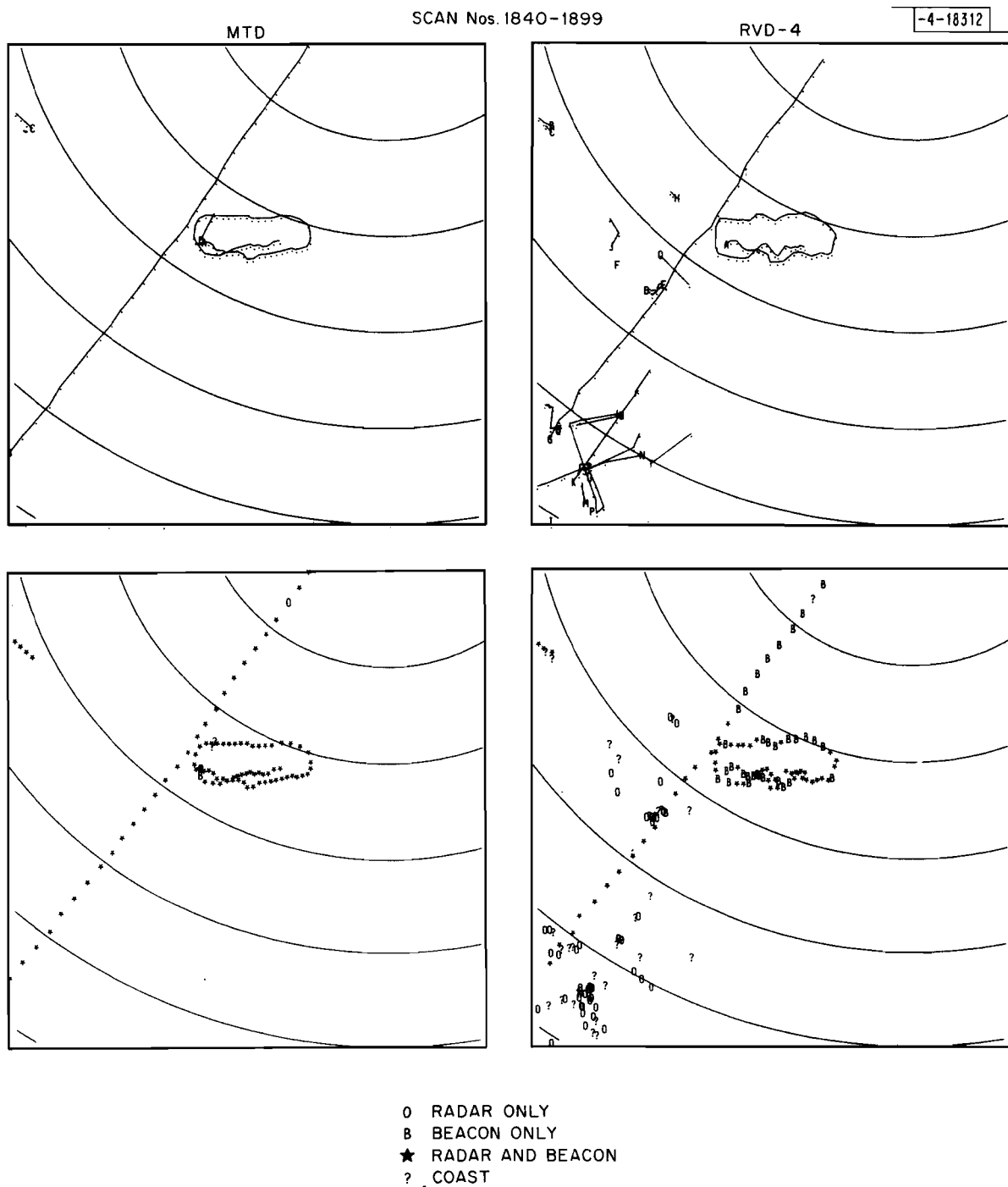


Fig.V-13. MTD vs RVD-4, ARTS-III tracker output in rain.
(Scans 1840-1899, 6 August 1975).

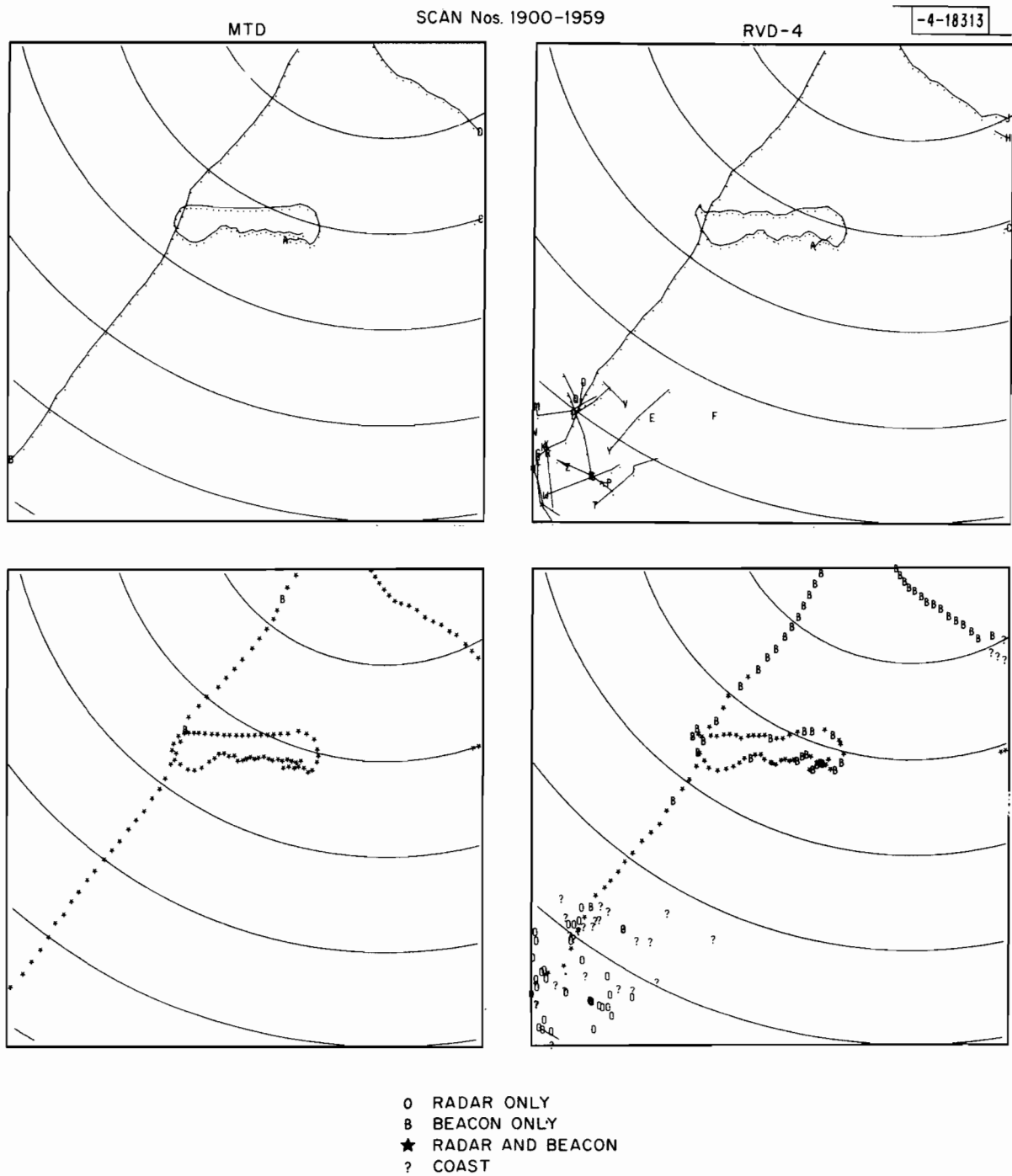


Fig.V-14. MTD vs RVD-4, ARTS-III tracker output in rain.
 (Scans 1900-1959, 6 August 1975).

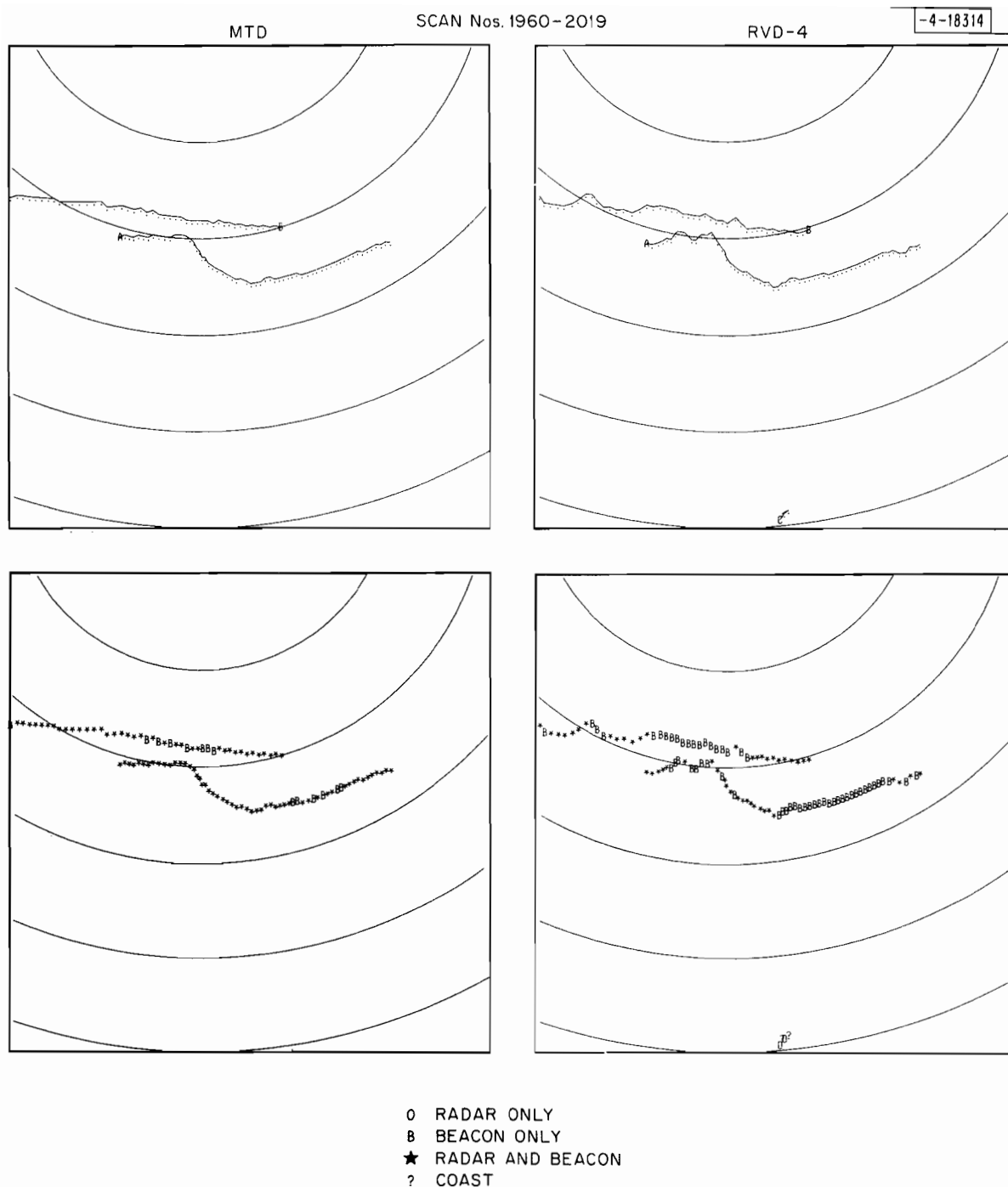


Fig.V-15. MTD vs RVD-4, ARTS-III tracker output in rain.
 (Scans 1960-2019, 6 August 1975).

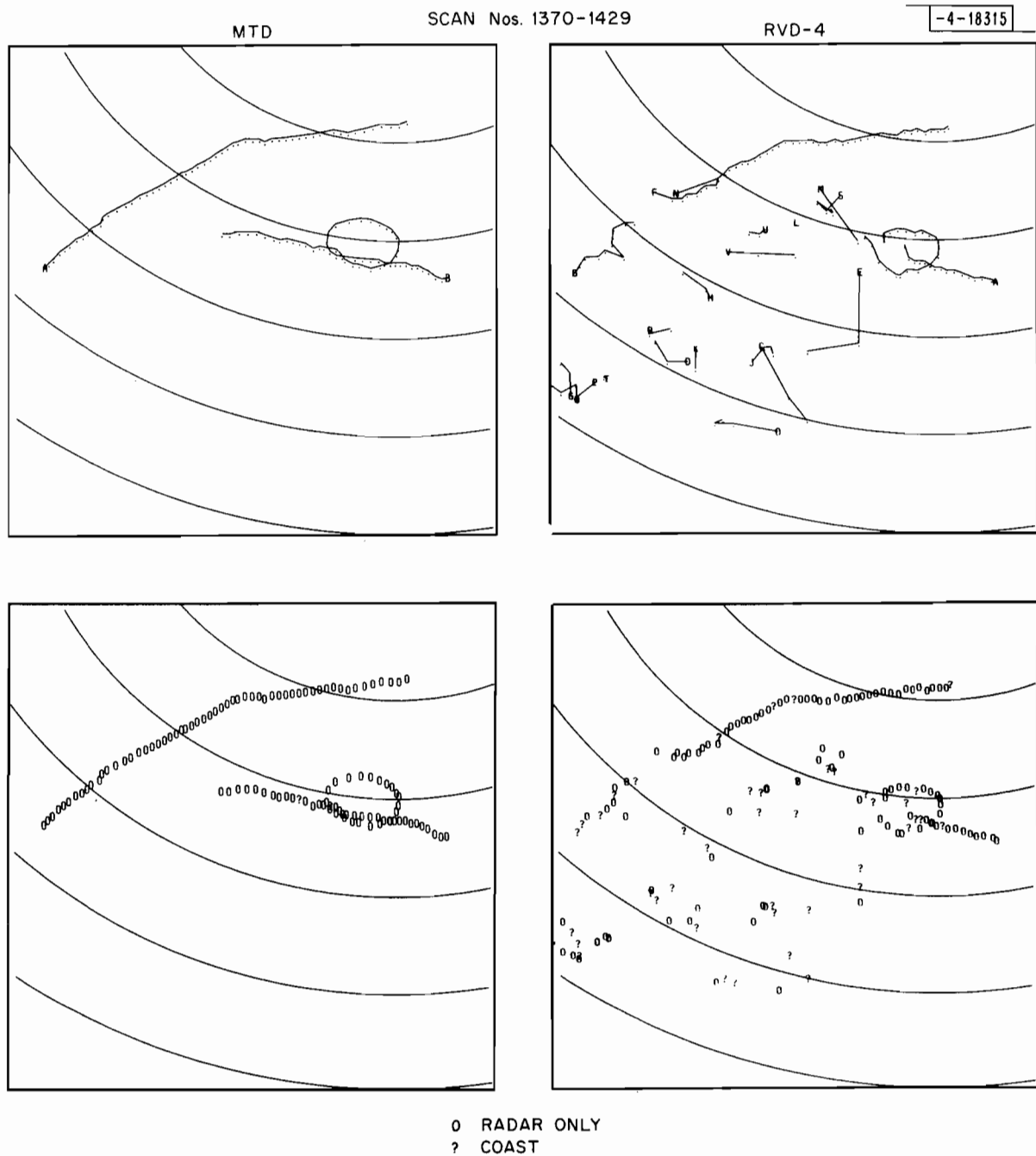


Fig.V-16. MTD, radar-only tracker output in rain. (Scans 1370-1429, 6 August 1975).

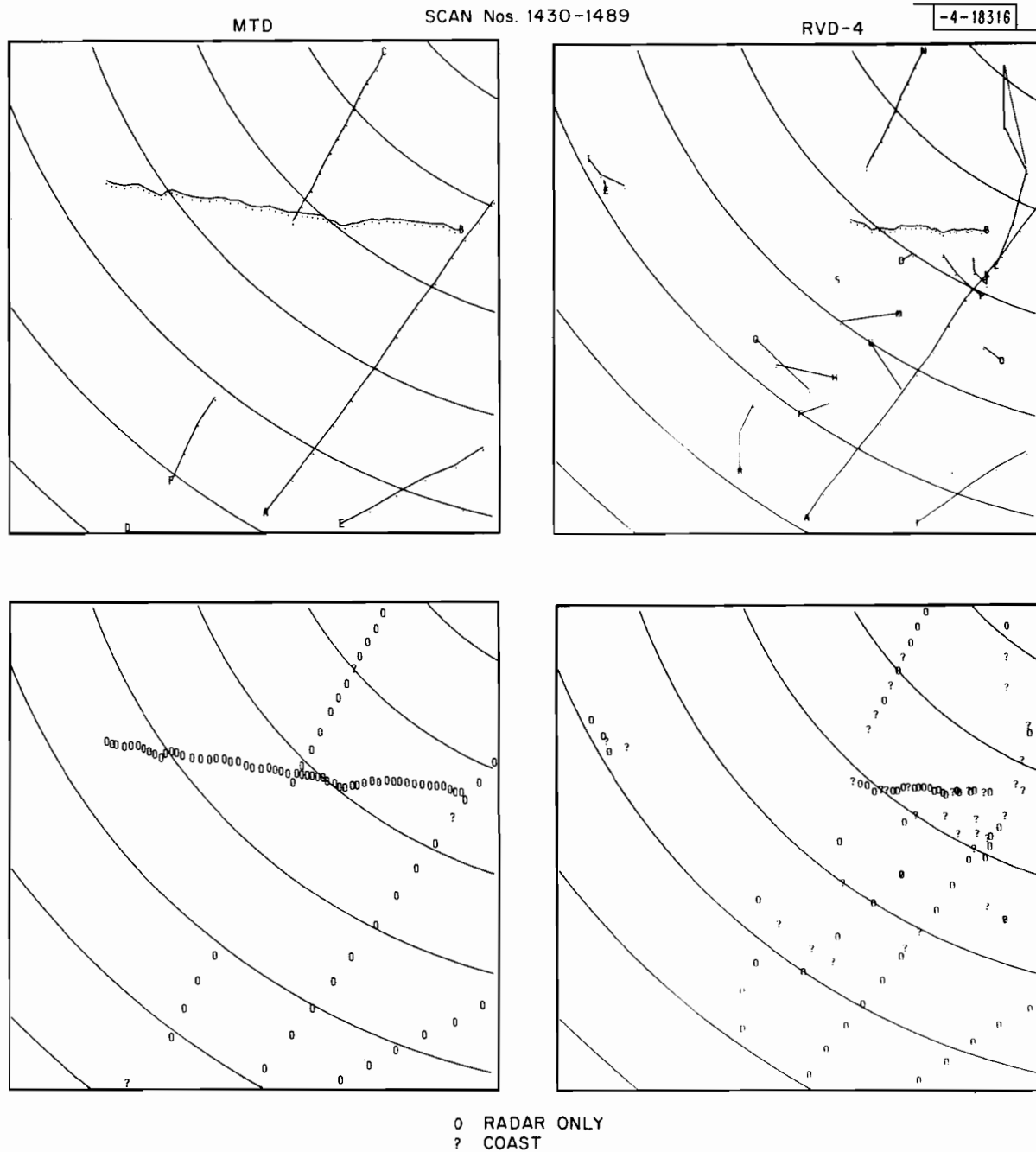


Fig.V-17. MTD, radar-only tracker output in rain. (Scans 1430-1489, 6 August 1975).

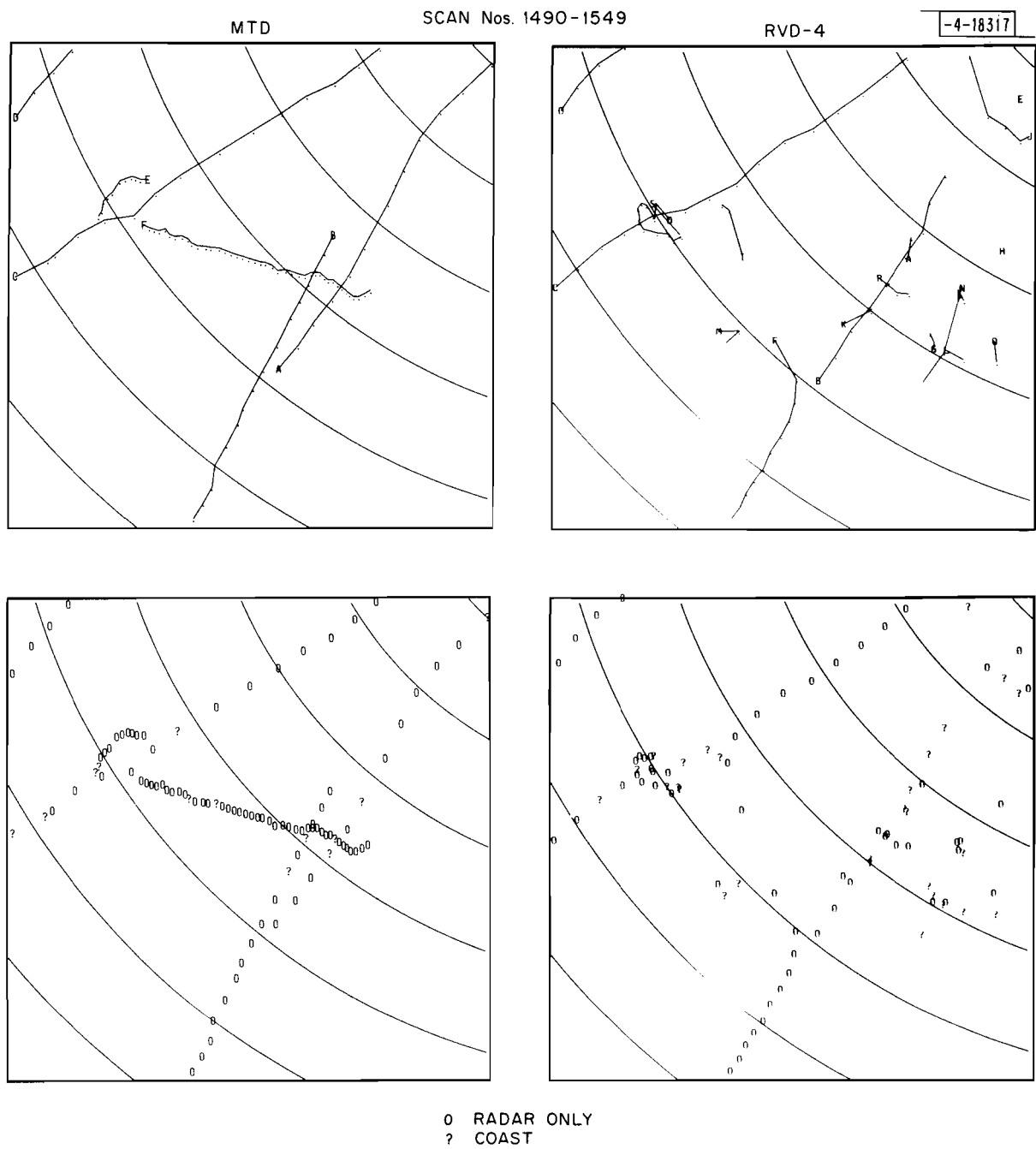


Fig.V-18. MTD, radar-only tracker output in rain. (Scans 1490-1549, 6 August 1975).

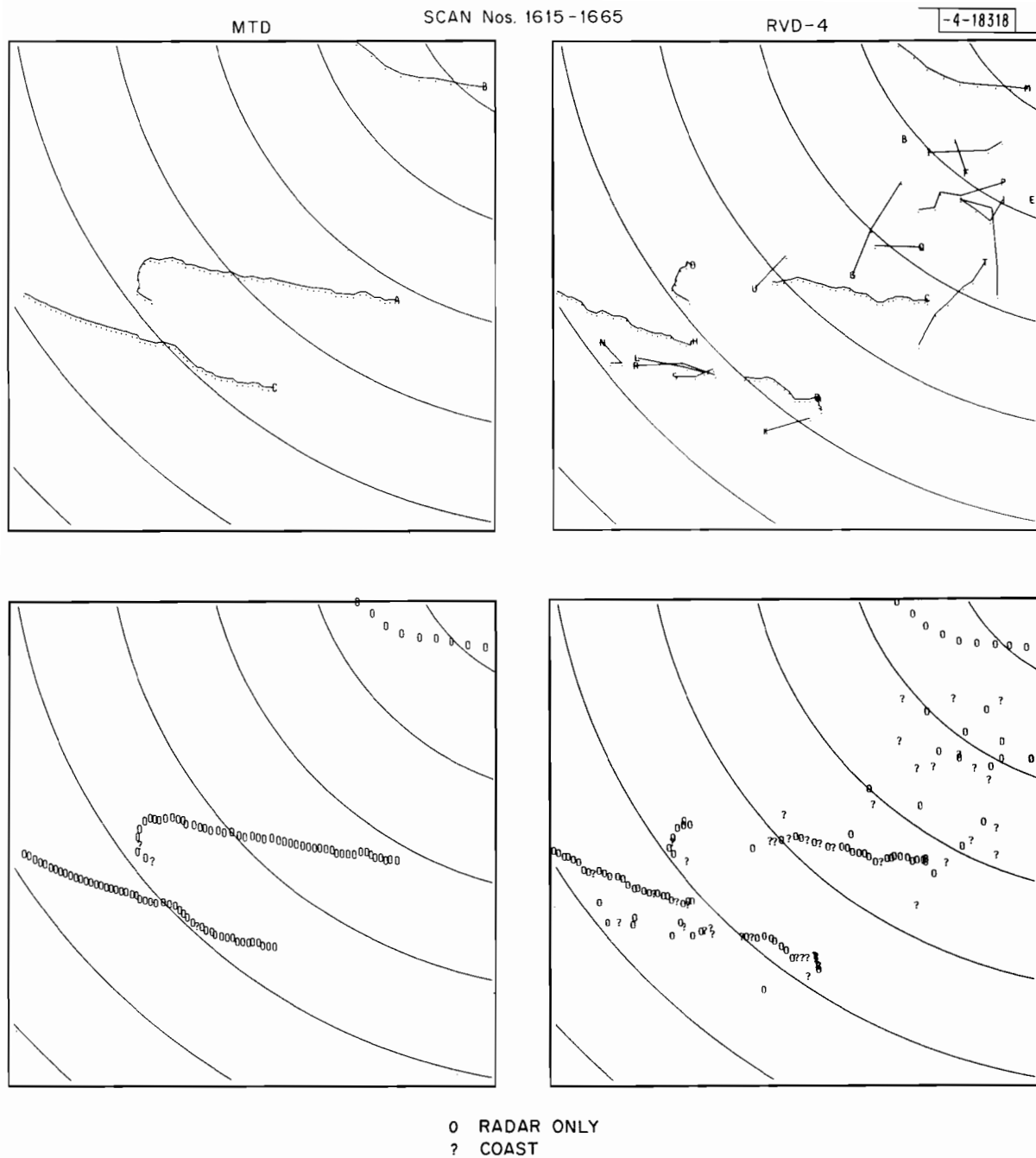


Fig.V-19. MTD, radar-only tracker output in rain. (Scans 1615-1665, 6 August 1975).

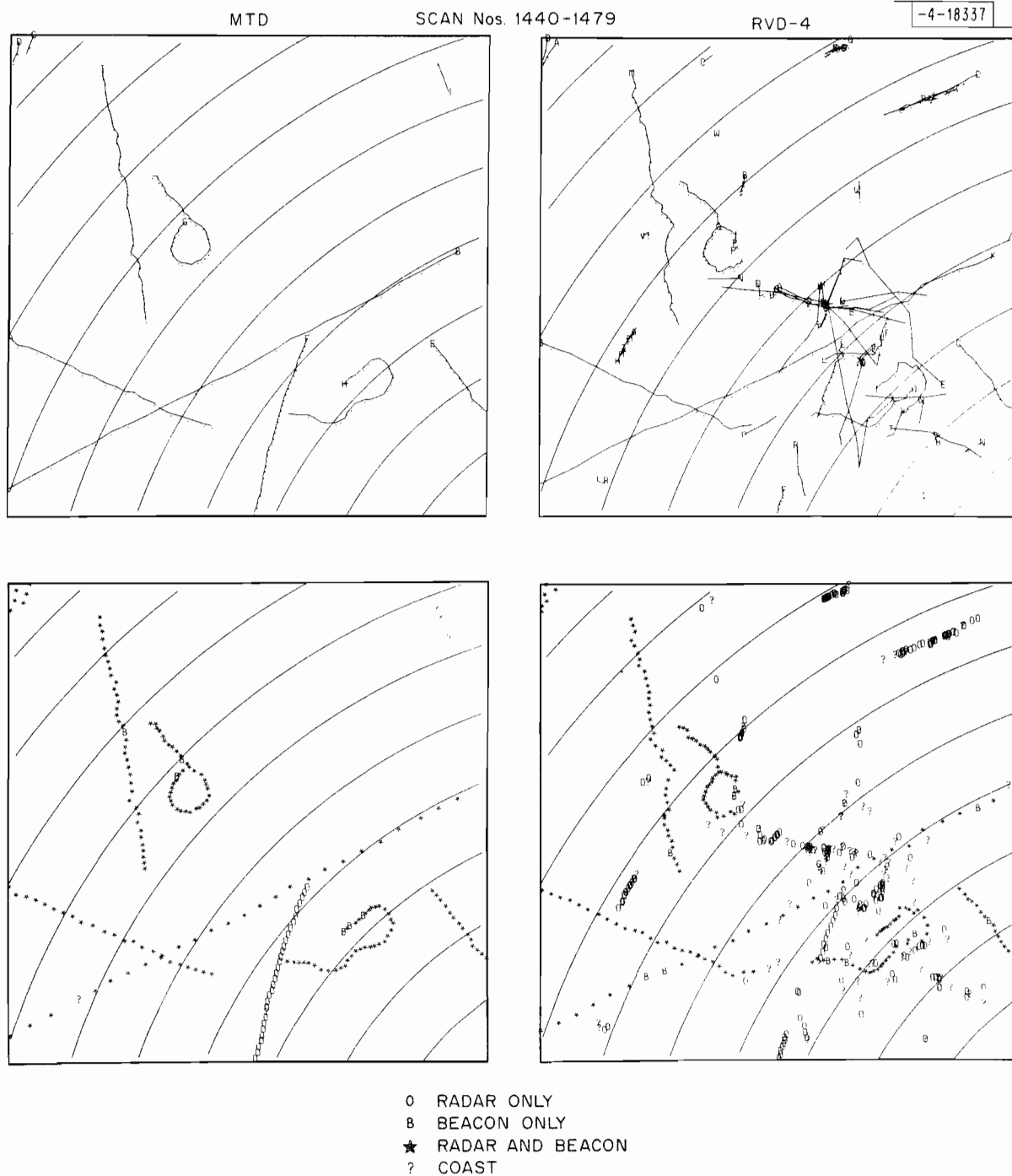


Fig.V-20. MTD/RVD-4, relative false alarm performance, radar/beacon report and track data (Scans 1440-1479, 6 August 1975).

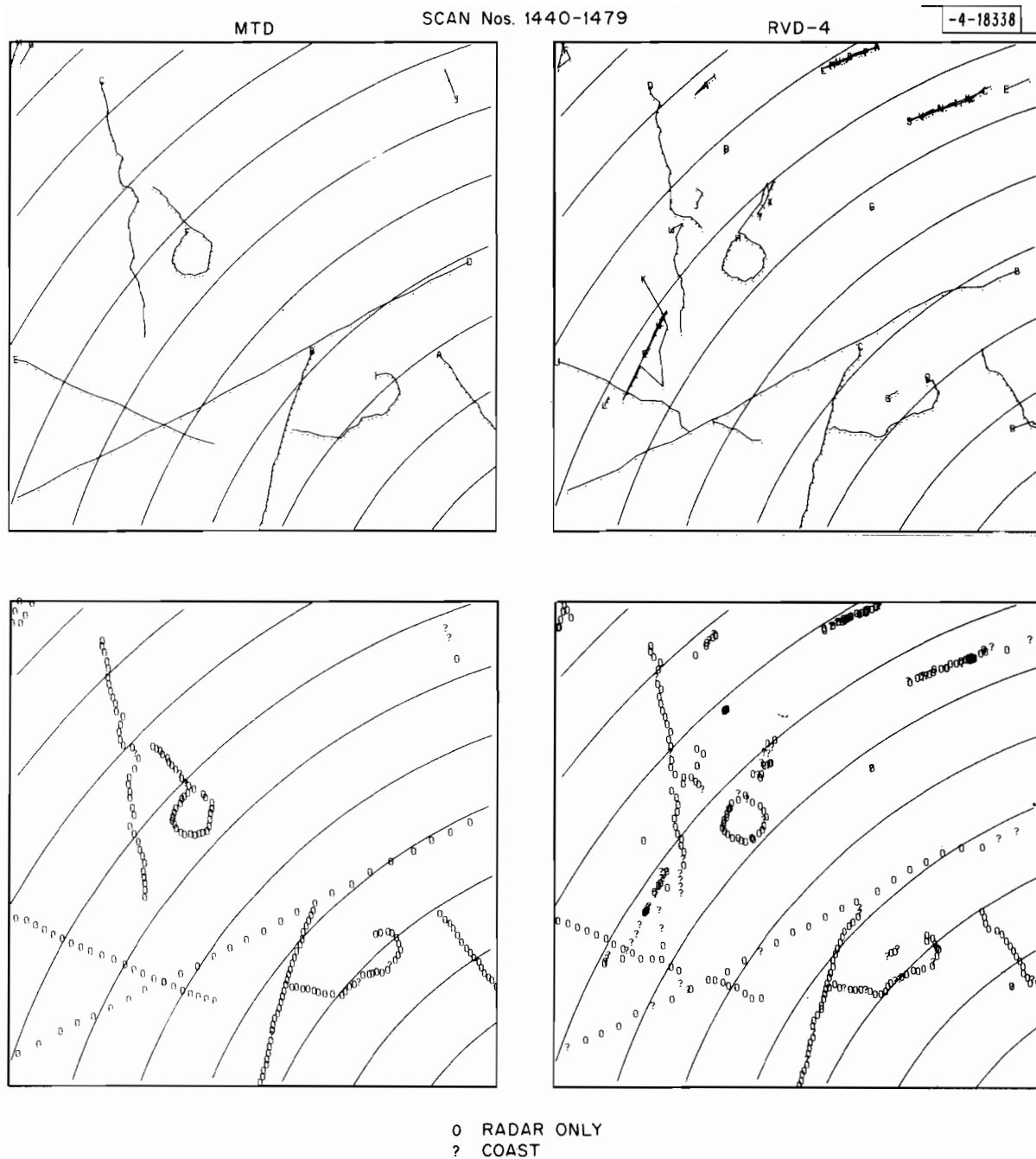
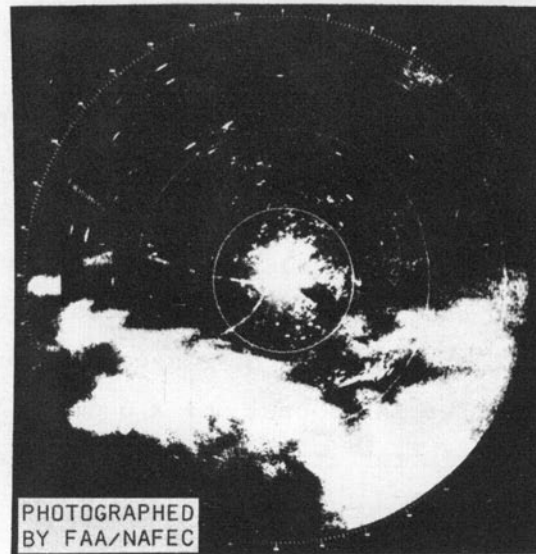


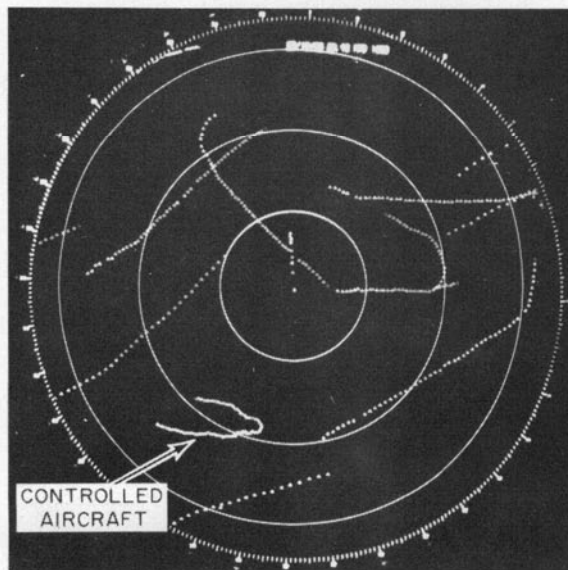
Fig.V-21. MTD/RVD-4, relative false alarm performance, automated tracker output beacon inhibited (Scans 1440-1479, 6 August 1975).

NORMAL VIDEO

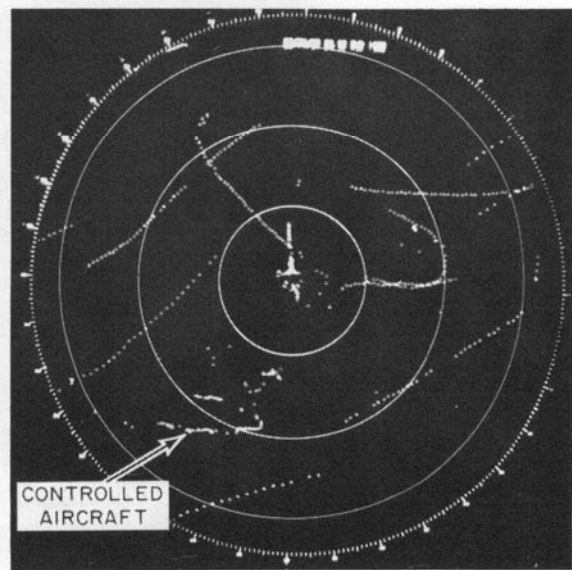
-4-18058



MTD



RVD-4



(5 nmi. Range Rings)

Fig.V-22. MTD/RVD-4, performance compared in rain clutter.

D. Subclutter Visibility Measurements with a Test Target Generator

1. General

The NAFEC site is a rather unfortunate one for demonstrating subclutter capability because there are only a few small areas for which ground clutter returns are observed. There are, however, areas of point returns which are relatively strong. These echos are from tall buildings in Atlantic City, Ventnor City and Margate, N.J. Echoes as strong as 70 dB above the system noise before STC are observed at ranges of 7 or 8^{*} nmi. The area of this patch of ground clutter is about 1 nmi x 6 nmi. Figure V-23 presents a digital map of the ground clutter at NAFEC with the patch used for these tests indicated.

2. Expected MTD Subclutter Visibility

The MTD is a linear system. Hence, the sensitivity to moving targets should be independent of the presence or absence of ground clutter so long as the ground clutter echo amplitude remains within the linear dynamic range of the system. The linear dynamic range of the MTD system at NAFEC was approximately 44.6 dB as measured at the analog-to-digital converters. Results presented in Reference 1 show that the MTD exhibited a probability of detection of 0.5 when the signal-to-noise ratio in the i-f channel is between 2.0 and 3.4 dB. Thus, the MTD is expected to provide a subclutter visibility^{**} of approximately 42 dB.

3. Expected ASR-7/RVD-4 Subclutter Visibility

The ASR-7/RVD-4 system employs limiting at i-f to control the amplitude of clutter sent to the 3-pulse MTI canceller. This limiting at i-f degrades the MTI performance of the radar by spreading the clutter spectrum. The expected subclutter visibility of this type of radar has been calculated to be about 23 dB (see References 1 and 10).

* These echos were attenuated to about 30 dB above system noise when the STC was applied.

** Subclutter visibility is defined as the ratio of clutter signal to target signal when the target signal is exactly superimposed on the clutter signal and producing a probability of detection of 0.5.

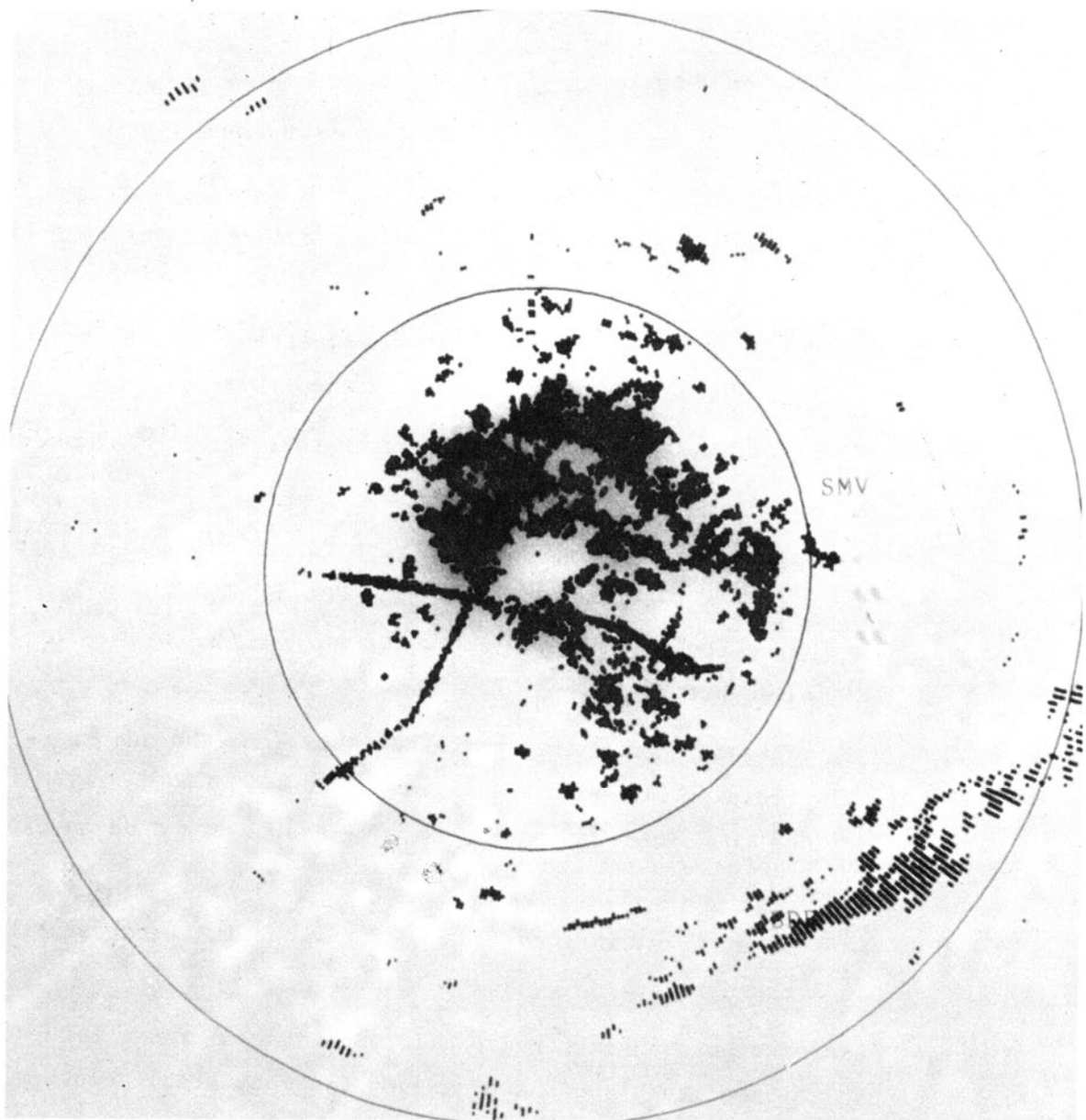


Fig.V-23. Digital map of ground clutter at NAFEC (5 mile range rings).

4. Test Methods

The subclutter visibility measurements (see Fig. V-24) were made with the radar connected to the antenna, the transmitter on and the antenna scanning normally. Basically, the method was to:

- (a) determine the range and azimuth of a large, isolated, fixed echo,
- (b) adjust the STC (or other front-end attenuator) until the echo was very nearly limited by the A/D converters,
- (c) superimpose the test target generator signal on the clutter signal,
- (d) reduce the amplitude of the test target signal until the blip-scan ratio observed on the PPI display was 0.5; observe the corresponding reading on the precision waveguide attenuator.
- (e) increase the amplitude of the test signal by adjusting the precision attenuator until amplitude of the test signal and the clutter signal were equal as observed on an expanded A-scope display of the i-f output.

The measured subclutter visibility is the difference in dB between the attenuator readings taken in steps (d) and (e) above.

Precise measurement of subclutter capability using real radar returns is difficult because the amplitude and phase of even the most stable clutter echoes fluctuate slowly. These fluctuations, as observed on a bipolar video channel, are estimated to cause variations in I or Q signals as great as 2 dB during the time required to make a subclutter measurement.

There are other potential sources of error, particularly inaccurate positioning of the test target over the clutter. During the NAFEC tests the procedure used was to offset the test target in range by a few pulsewidths in order to match the azimuth of the test target and that of the clutter. Once

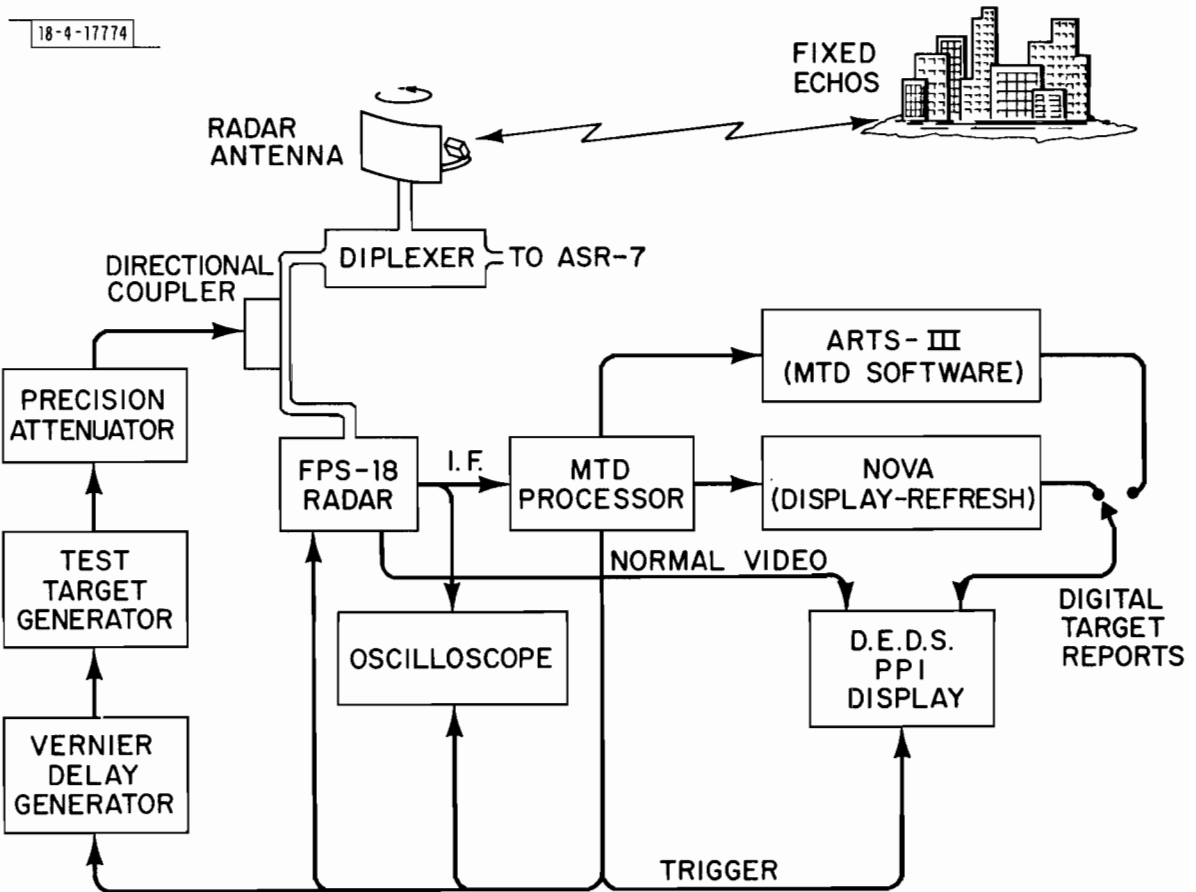


Fig.V-24. SCV test set up.

the azimuth was set exactly, the two echoes were superimposed in range by varying the range of the test target while observing an expanded A-scope presentation of the i-f signal. The test signal generator used for these tests did not have adequate range setting resolution, hence a vernier delay generator was added at the test target generator trigger input.

Some MTI systems can be adjusted to produce clutter residue which may lead to optimistic subclutter readings in tests of this kind. In these tests this possible source of error was eliminated by checking that the MTD produced no clutter residue detections in all the measurements made with no target signal.

5. Test Results

The procedure described above was carried out several times at each of a number of doppler velocities of the test target for both the FPS-18/MTD system and the ASR-7/RVD-4 system. Results - in agreement with theory - are presented graphically in Fig. V-25. The FPS-18/MTD has a subclutter visibility about 20 dB greater than that of the ASR-7/RVD-4. In addition, the MTD has even better subclutter visibility near zero doppler and the blind speed because of the greater number of pulses integrated coherently.

E. Detection of Aircraft in Ground Clutter

1. Test Flight - 12 August 1975

As mentioned in the previous section, there is a limited amount of ground clutter in the NAFEC area, the main region being a 1 nmi x 6 nmi strip along the New Jersey coastline about 8 miles SE of the TFAST site. On 12 August 1975, a Piper Cherokee was flown over this region of ground clutter for two hours to test the detection performance of the MTD and the RVD-4 in the presence of ground clutter. As with the precipitation tests, the interactive graphics programs were used to examine the data. Thirty scan blip-scan ratios of the MTD and RVD-4 radar reports are presented in Fig. V-26.

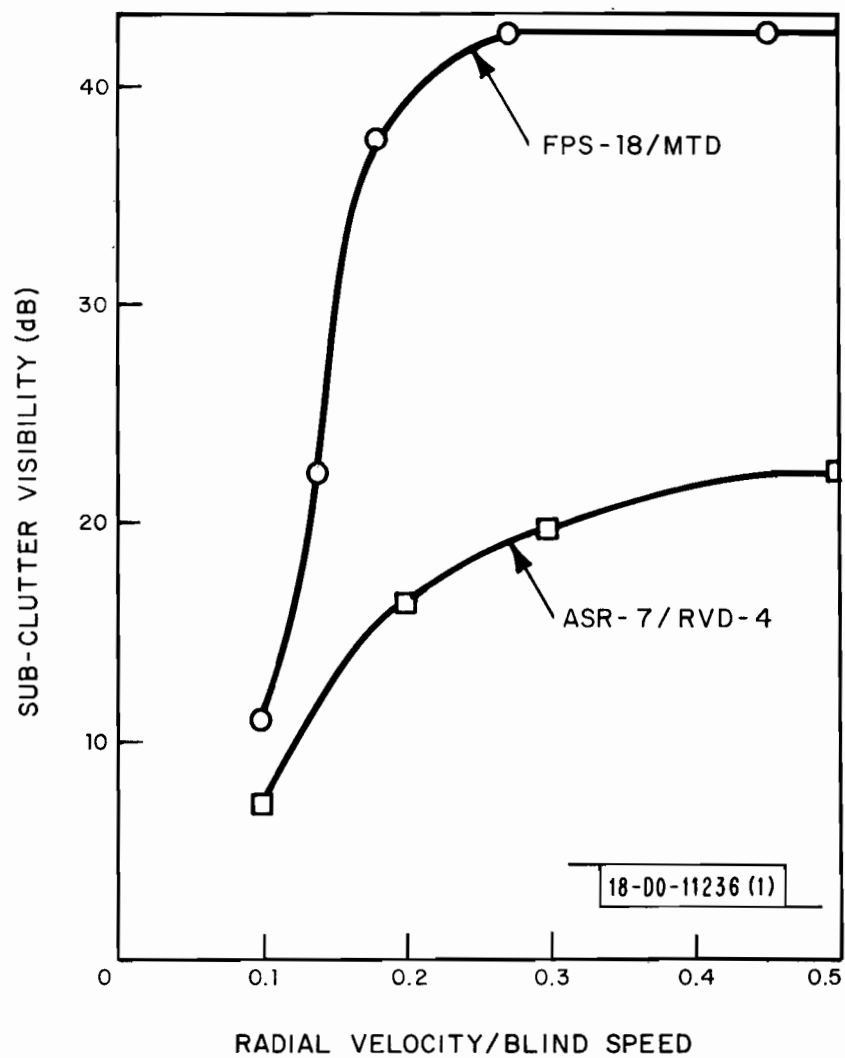


Fig.V-25. Subclutter visibility for $P_D = 0.5$ (measured).

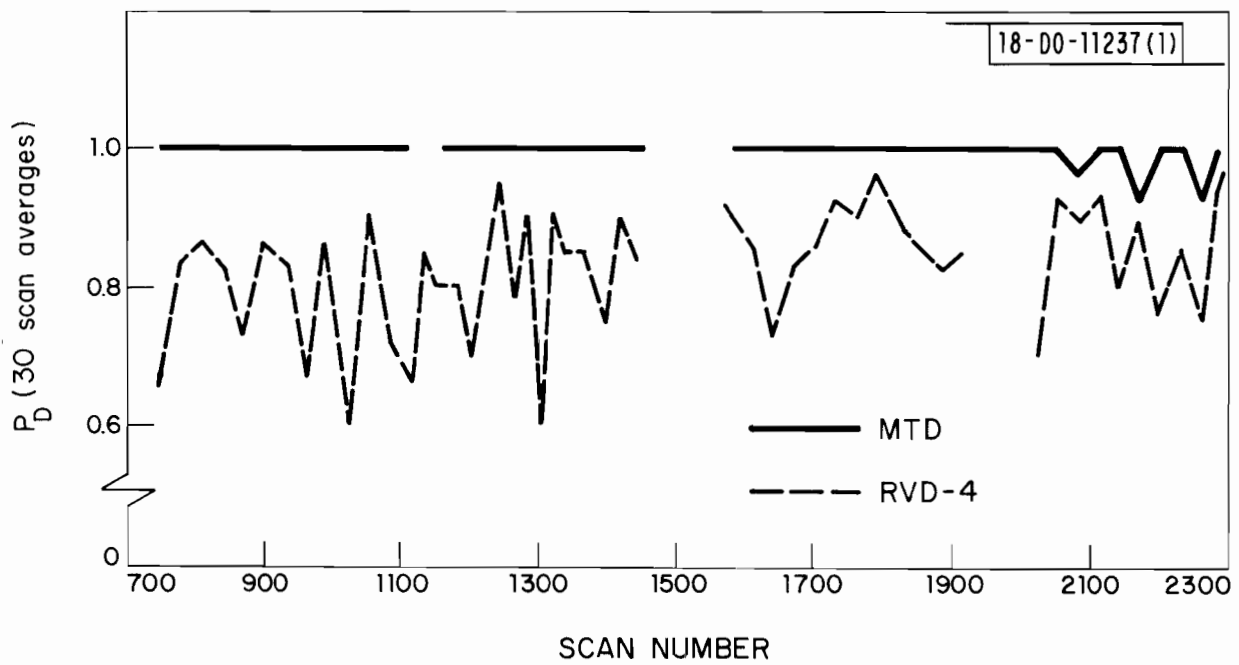


Fig.V-26. Blip/scan ratio during ground clutter test (12 August 1975).

The MTD detected the test aircraft on all but five of the more than 1200 scans of the test flight (a blip-scan ratio of 0.996). In addition, there were neither false tracks nor excessive false alarms caused by the ground clutter. The average blip scan ratio of the RVD-4 data was 0.82. The missed detections by the RVD-4 were correlated sufficiently from scan to scan to cause the ARTS-III tracker to be either very inaccurate in predicting track positions or to drop the track entirely.

Figures V-27 through V-38 present 40 scan segments of the ground clutter test flight. These Figures display, for both the MTD and RVD-4 processed data, the radar report data and the radar plus beacon ARTS-III automated tracker output. In several of the figures the test aircraft was flying tangentially through the ground clutter. The test aircraft is marked in the figures, and was flying at an altitude of 1000 feet during the test.

The MTD data was also processed through the ARTS-III tracker with the beacon data inhibited. The tracking results are equivalent to those obtained when the beacon data was used. Figures V-39 through V-42 present the ARTS-III tracker output for the MTD data in Figs. V-27 through V-30 when the beacon data was inhibited. Finally, in Fig. V-43 a comparison is shown of MTD and RVD-4 radar only tracking while the test aircraft is flying tangentially through the ground clutter. The normal video of the radar is also shown to display the location of the ground clutter. Note the excessive ground clutter induced false tracks for the RVD-4 at ranges less than 5 nmi.

2. Conclusions

The small test aircraft (nose-on cross section of about 1 m^2) was flown over the ground clutter near Atlantic City. The average detection probabilities of the MTD and RVD-4 were 0.995 and 0.82 respectively. The RVD-4 missed detections were highly correlated from scan to scan causing the tracker to drop track on many occasions.

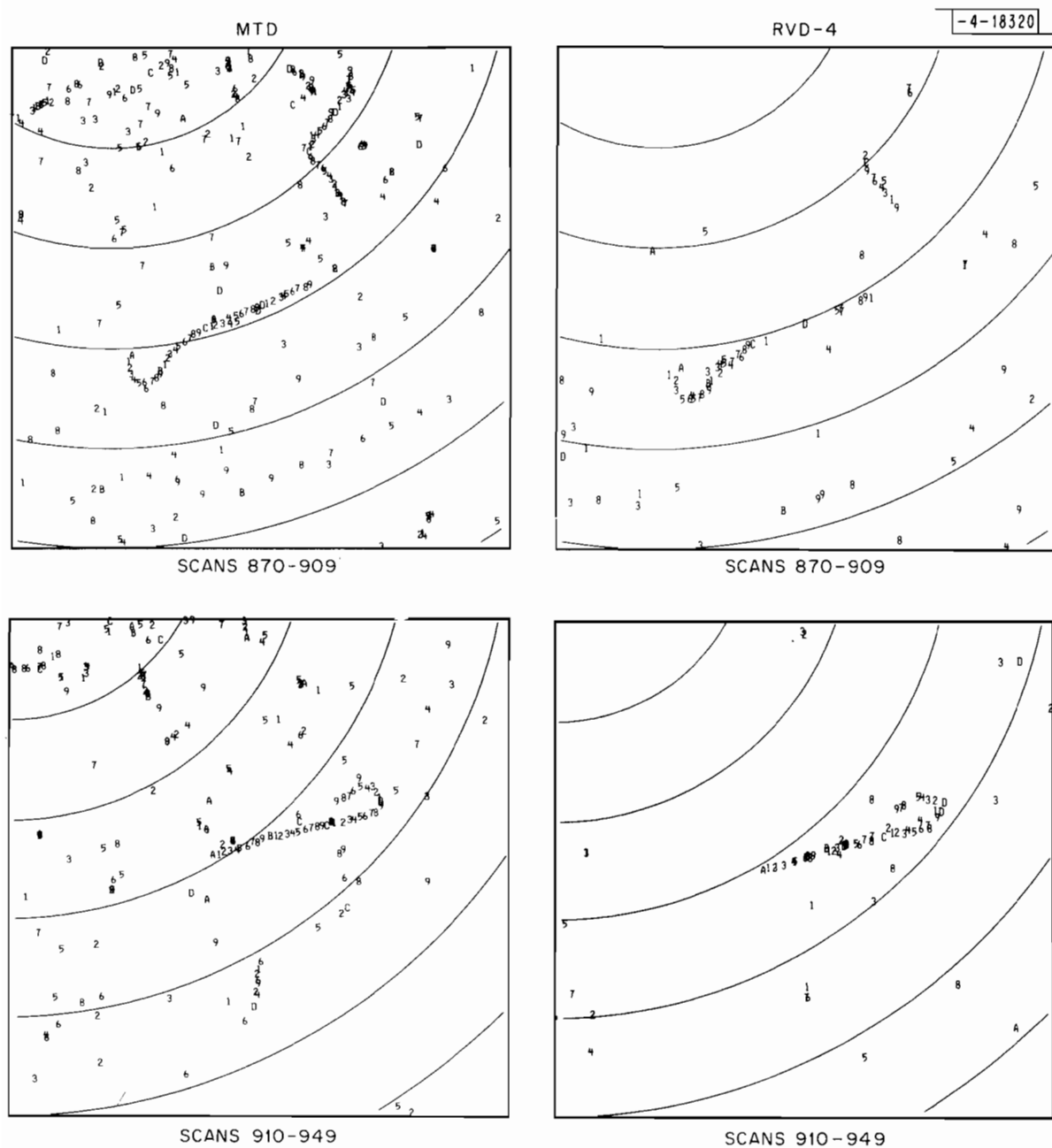
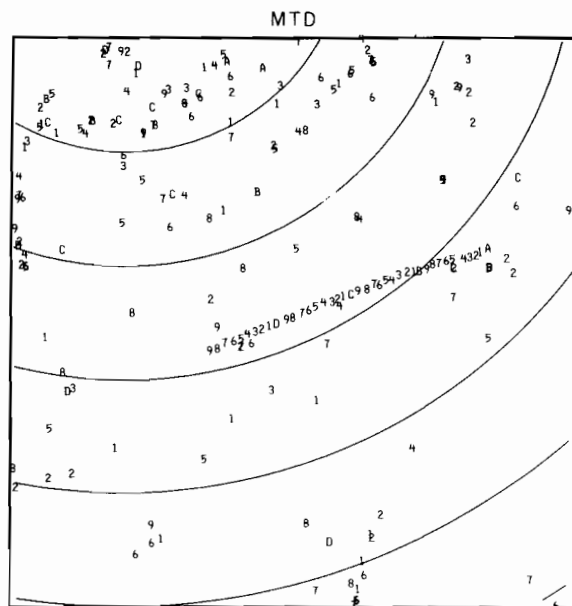
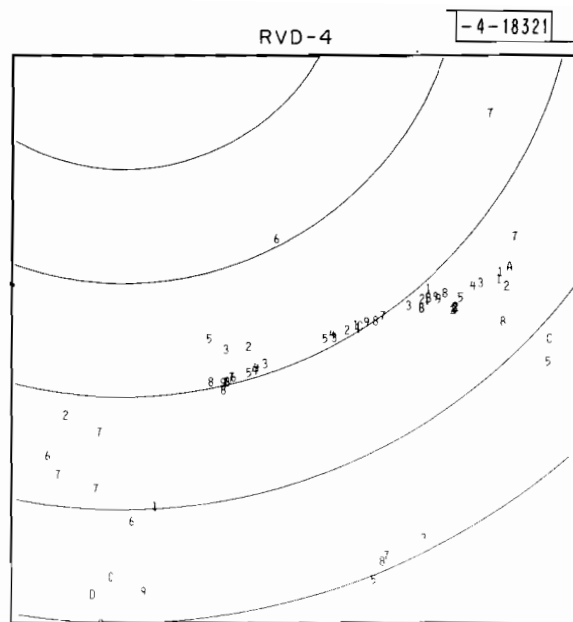


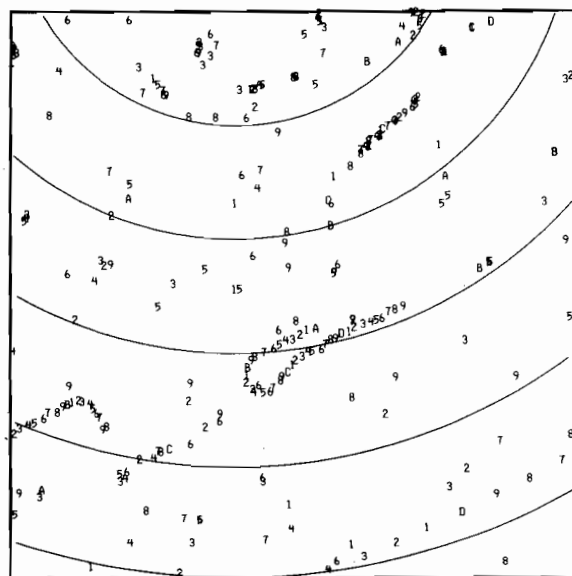
Fig.V-27. MTD vs RVD-4, radar reports in ground clutter. (Scans 870-909 and 910-949, 12 August 1975).



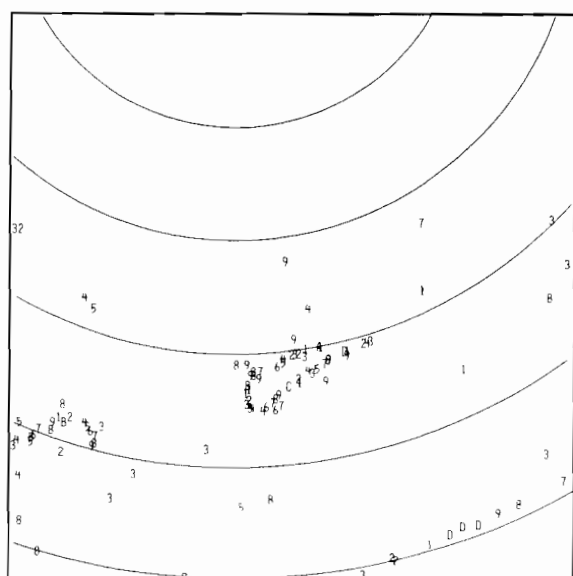
SCANS 950-989



SCANS 950-989



SCANS 990-1029



SCANS 990-1029

Fig.V-28. MTD vs RVD-4, radar reports in ground clutter.
(Scans 950-989 and 990-1029, 12 August 1975).

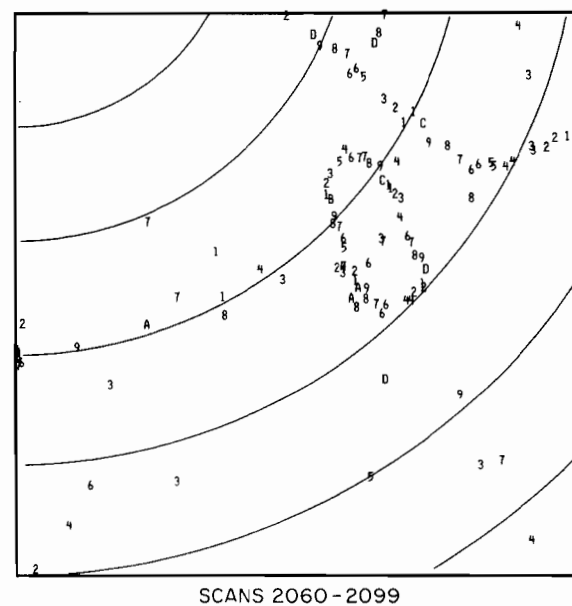
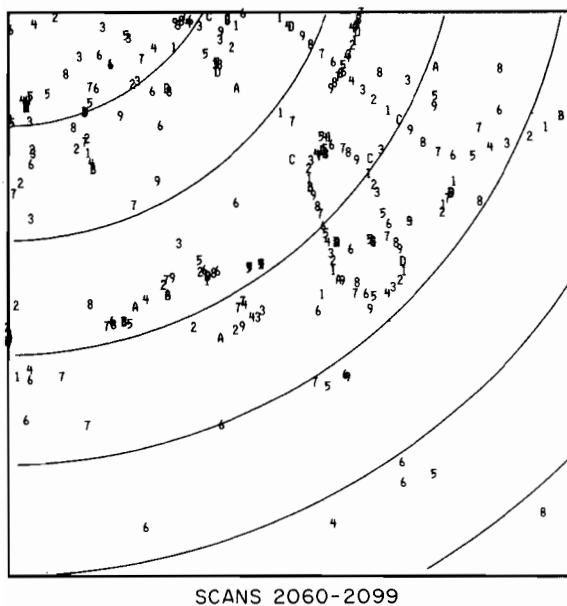
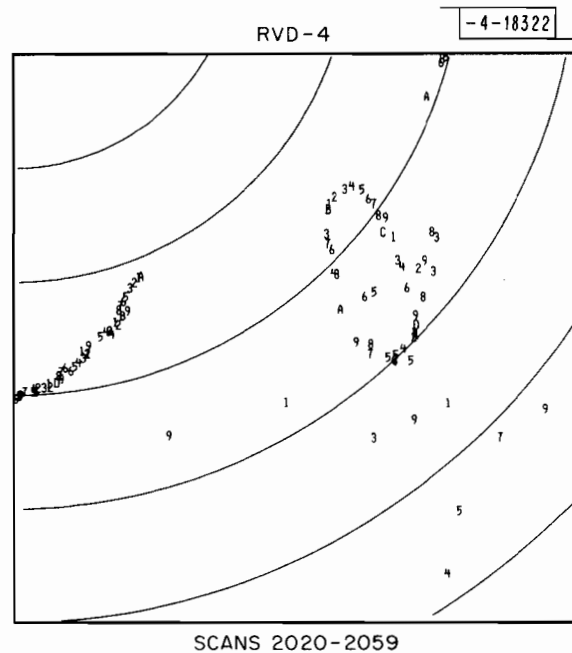
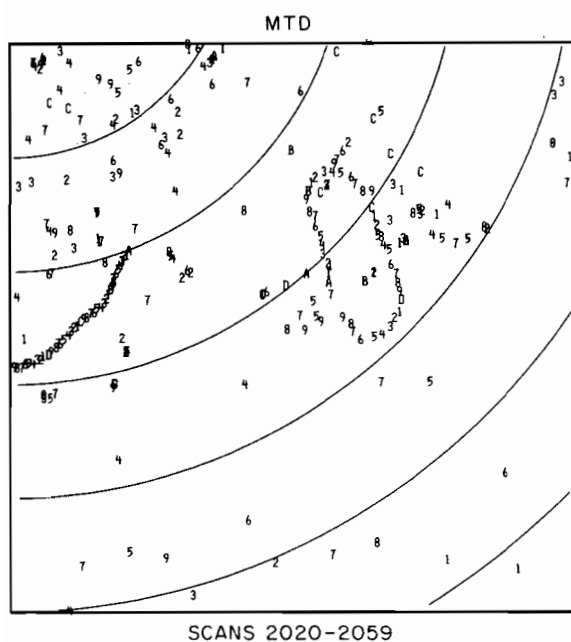
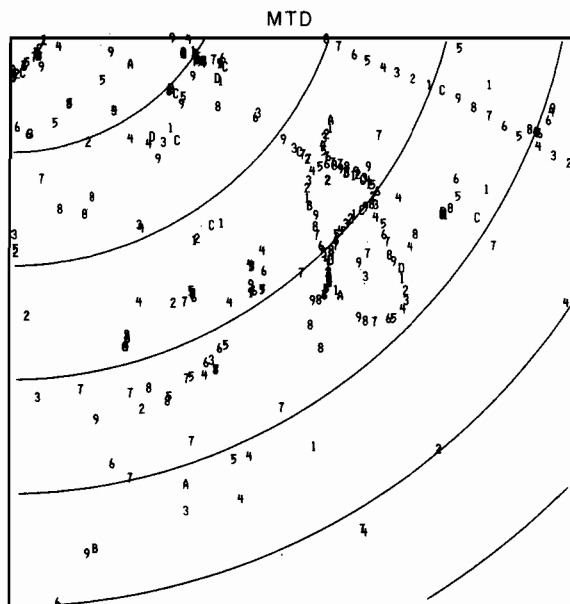
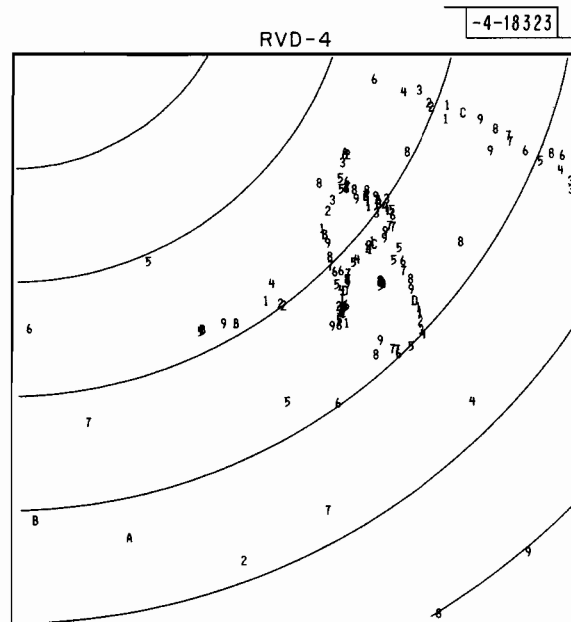


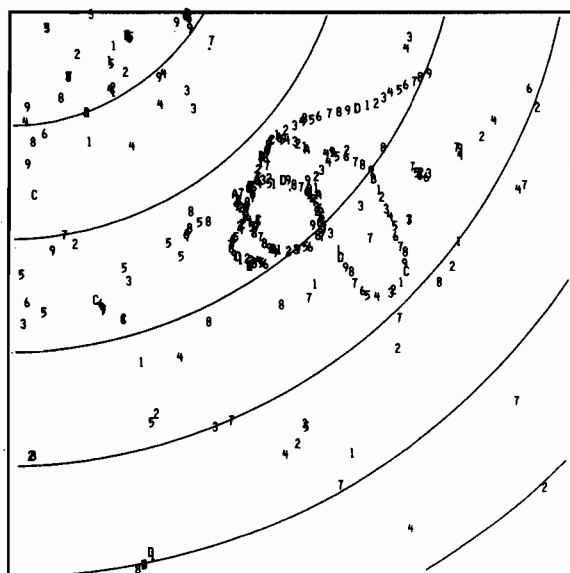
Fig.V-29. MTD vs RVD-4, radar reports in ground clutter.
(Scans 2020-2059 and 2060-2099, 12 August 1975).



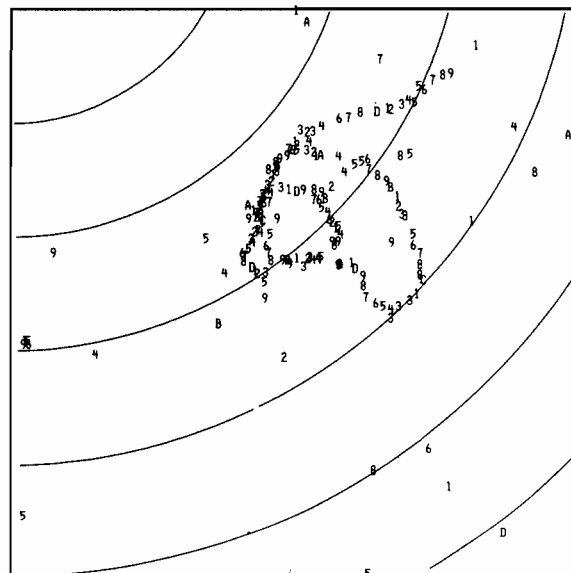
SCANS 2100-2139



SCANS 2100-2139



SCANS 2230-2269



SCANS 2230-2269

Fig.V-30. MTD vs RVD-4, radar reports in ground clutter.
(Scans 2100-2139 and 2230-2269, 12 August 1975).

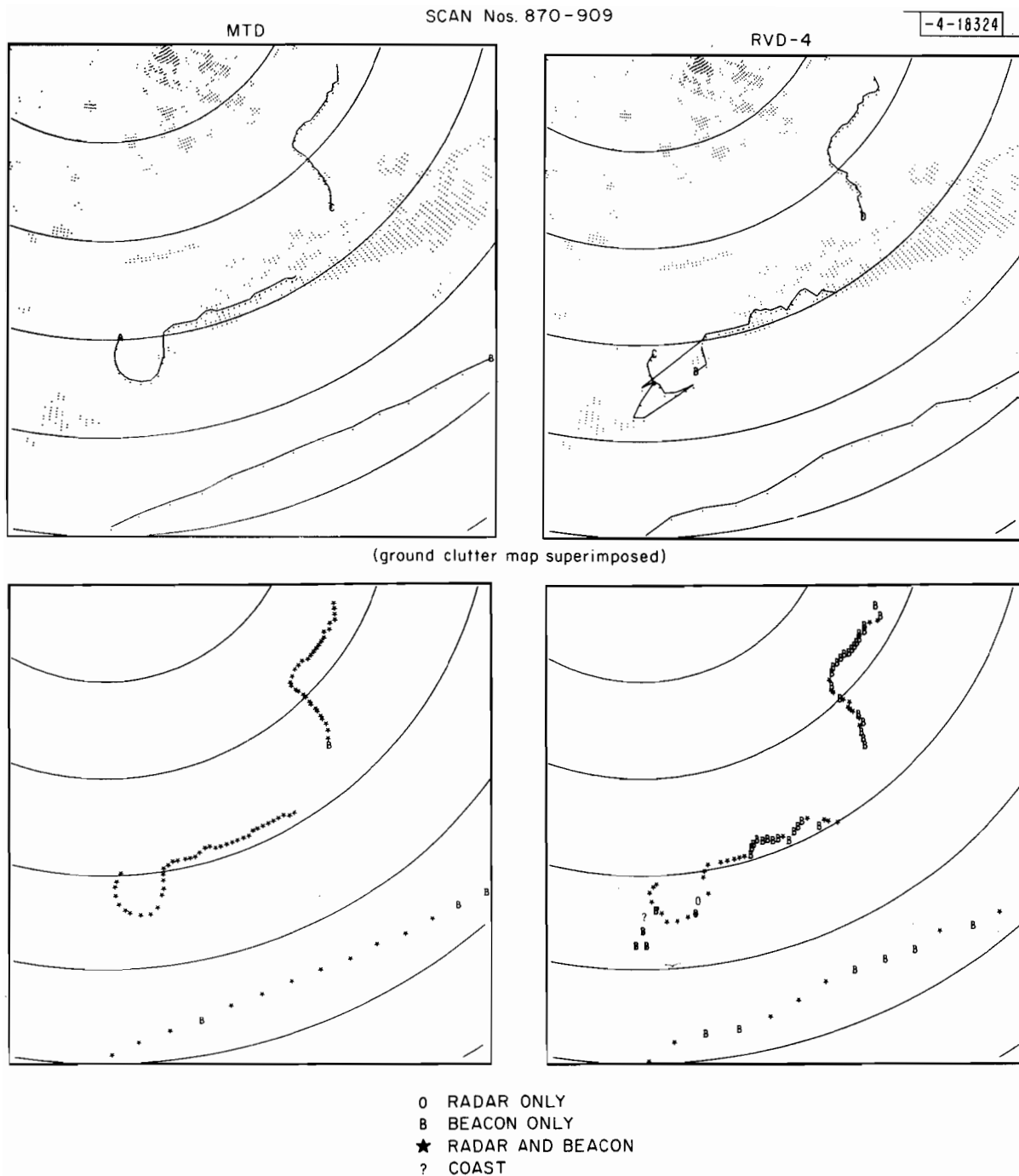


Fig.V-31. MTD vs RVD-4, ARTS-III tracker output in ground clutter.
(Scans 870-909, 12 August 1975).

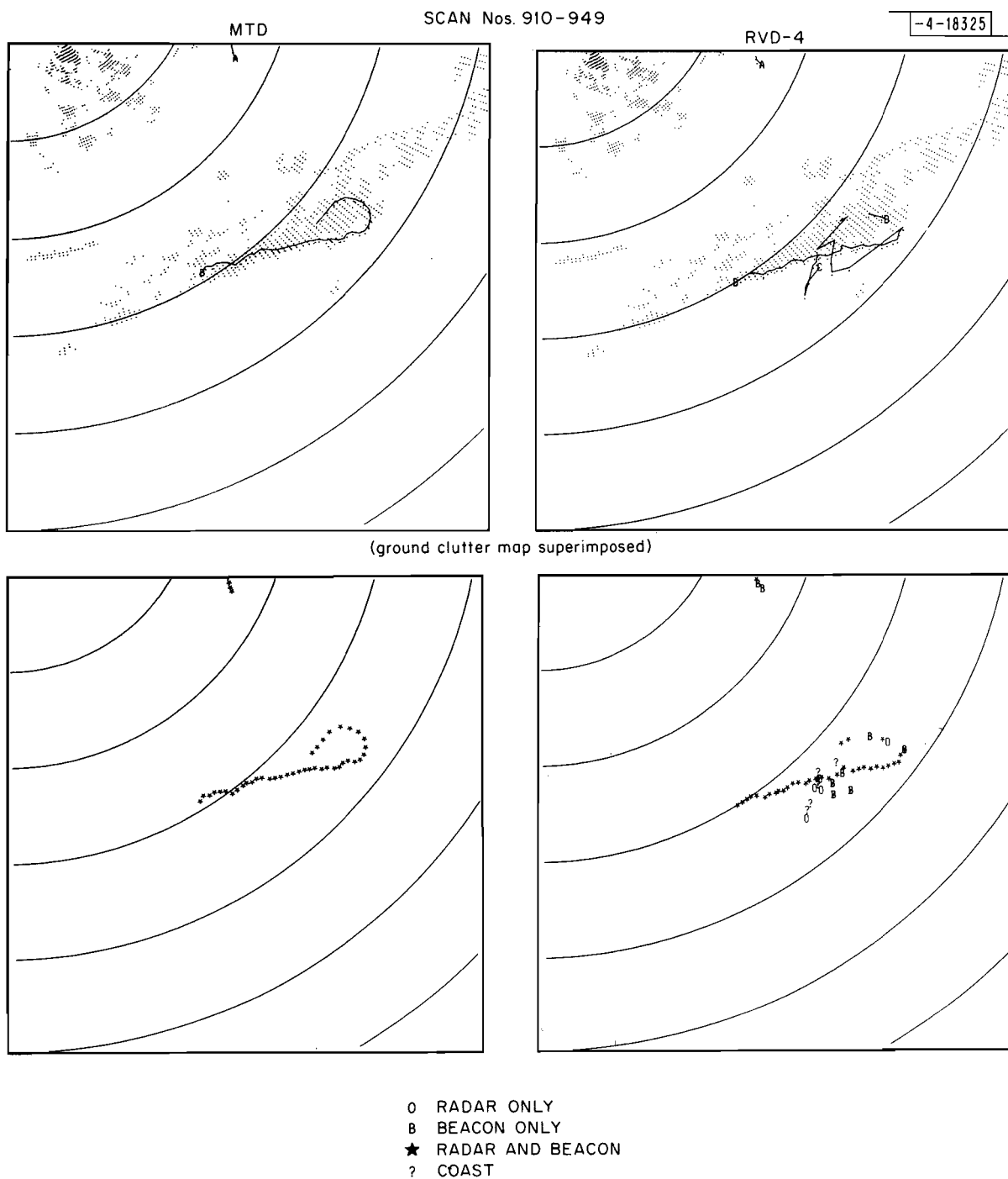


Fig.V-32. MTD vs RVD-4, ARTS-III tracker output in ground clutter.
(Scans 910-949, 12 August 1975).

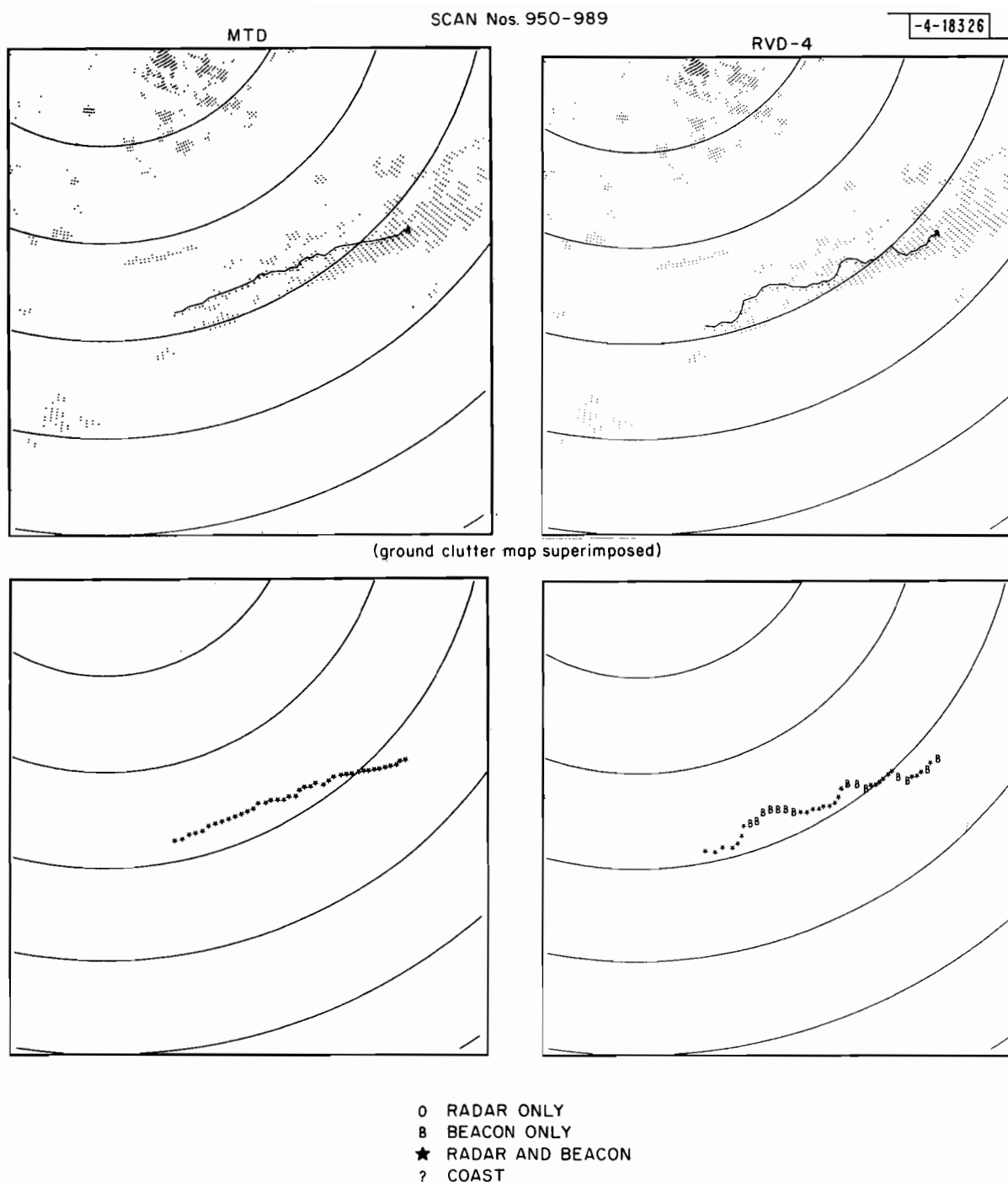


Fig.V-33. MTD vs RVD-4, ARTS-III tracker output in ground clutter.
 (Scans 950-989, 12 August 1975).

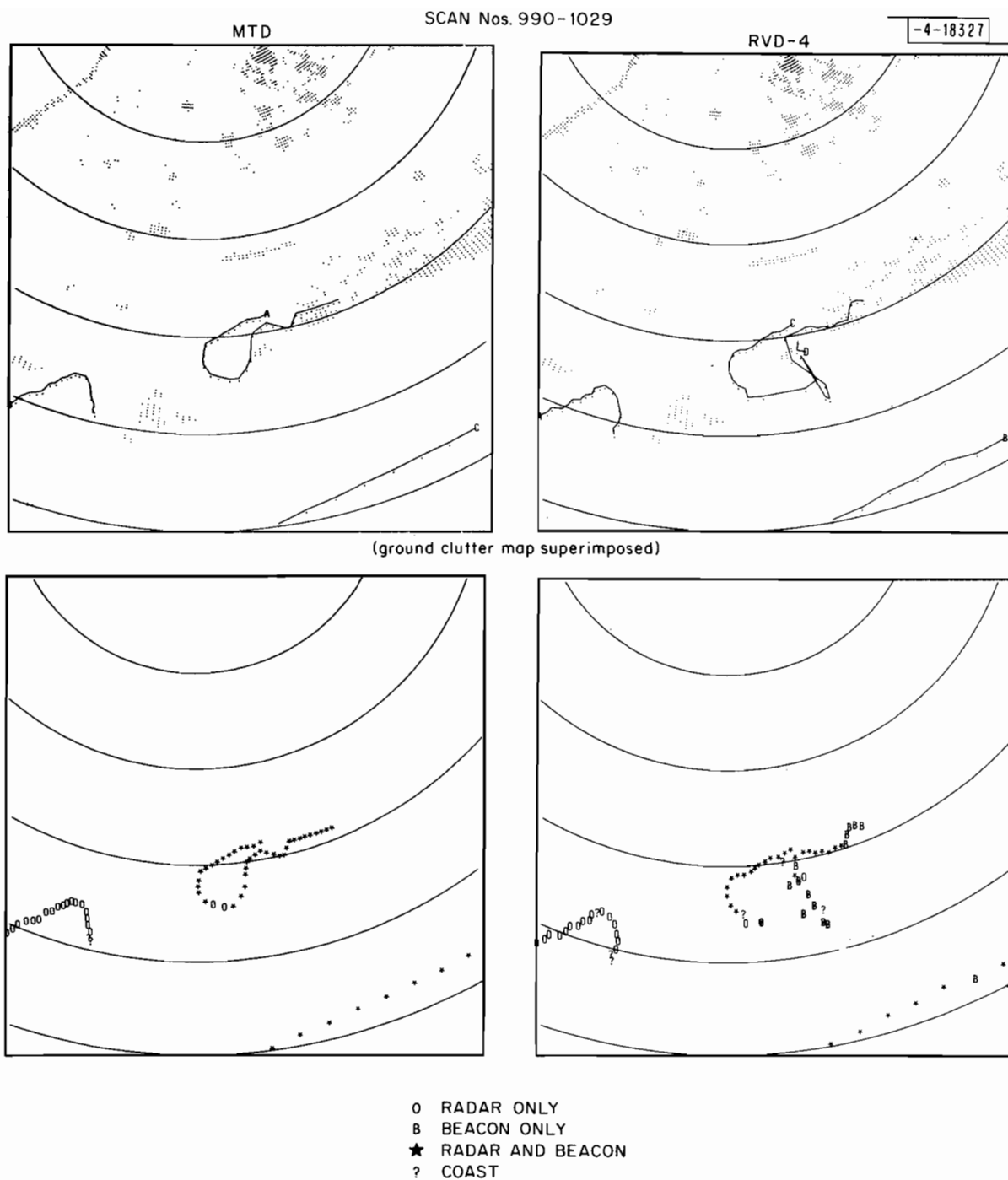


Fig.V-34. MTD vs RVD-4, ARTS-III tracker output in ground clutter.
(Scans 990-1029, 12 August 1975).

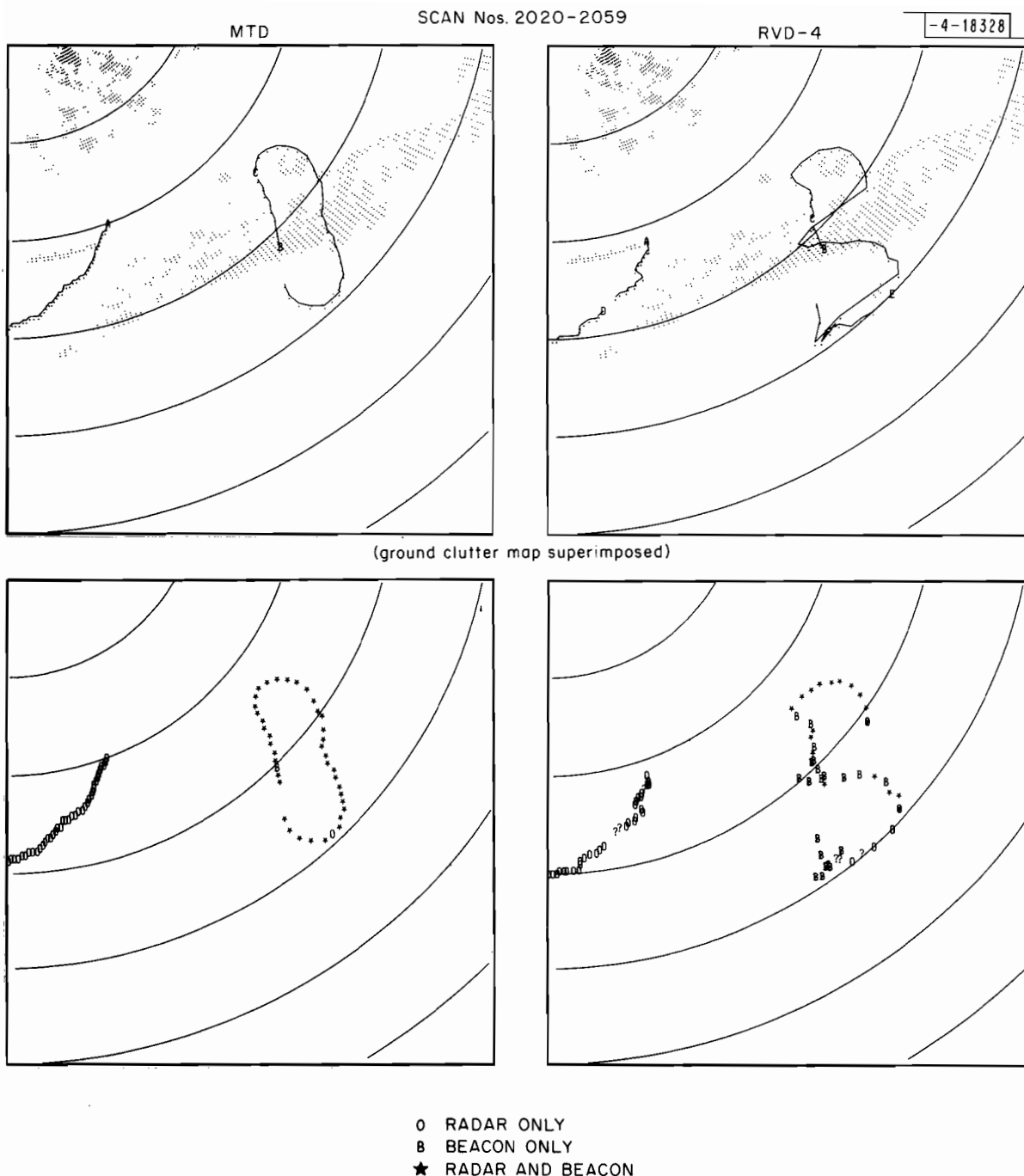


Fig.V-35. MTD vs RVD-4, ARTS-III tracker output in ground clutter.
(Scans 2020-2059, 12 August 1975).

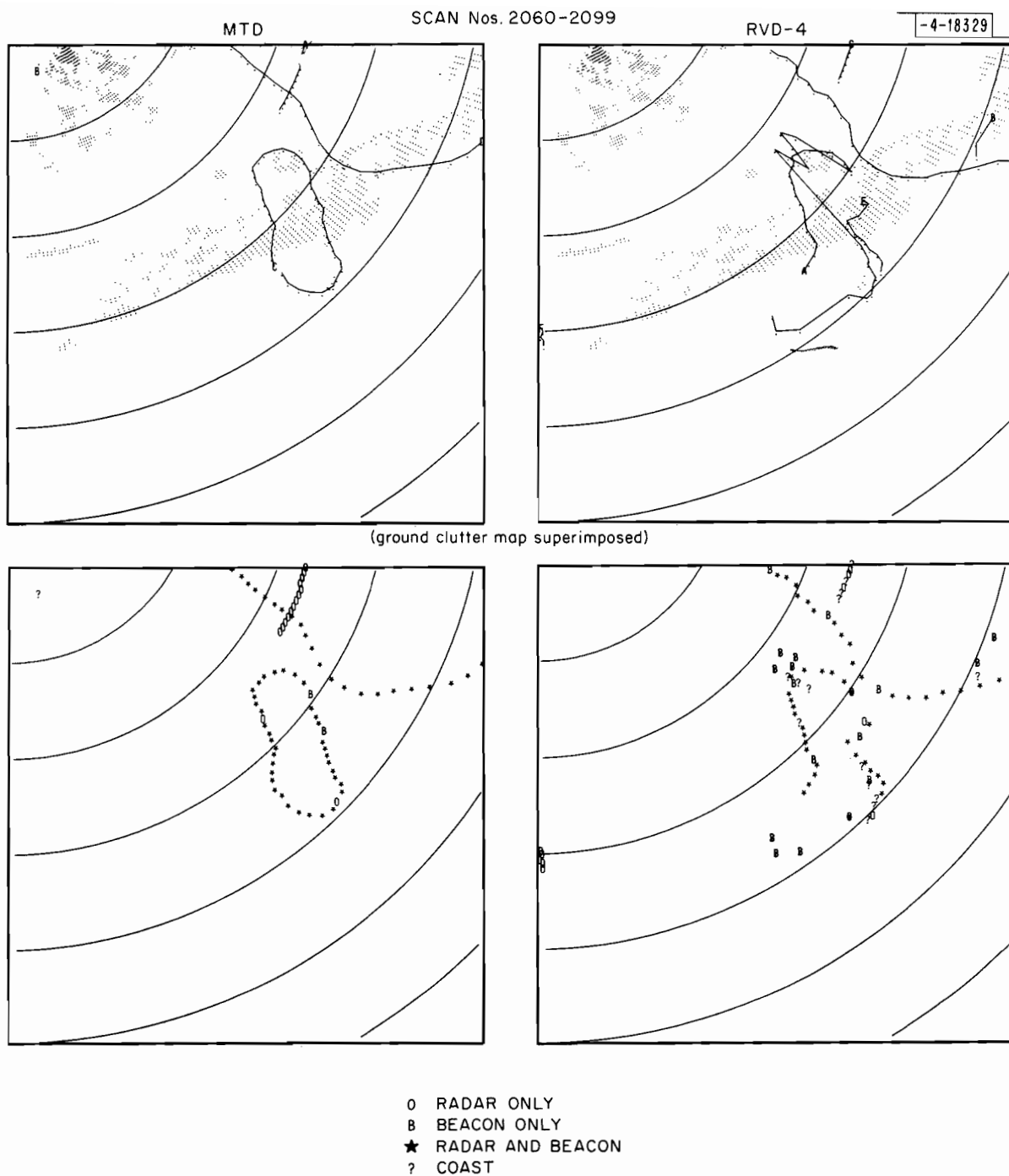


Fig.V-36. MTD vs RVD-4, ARTS-III tracker output in ground clutter.
(Scans 2060-2099, 12 August 1975).

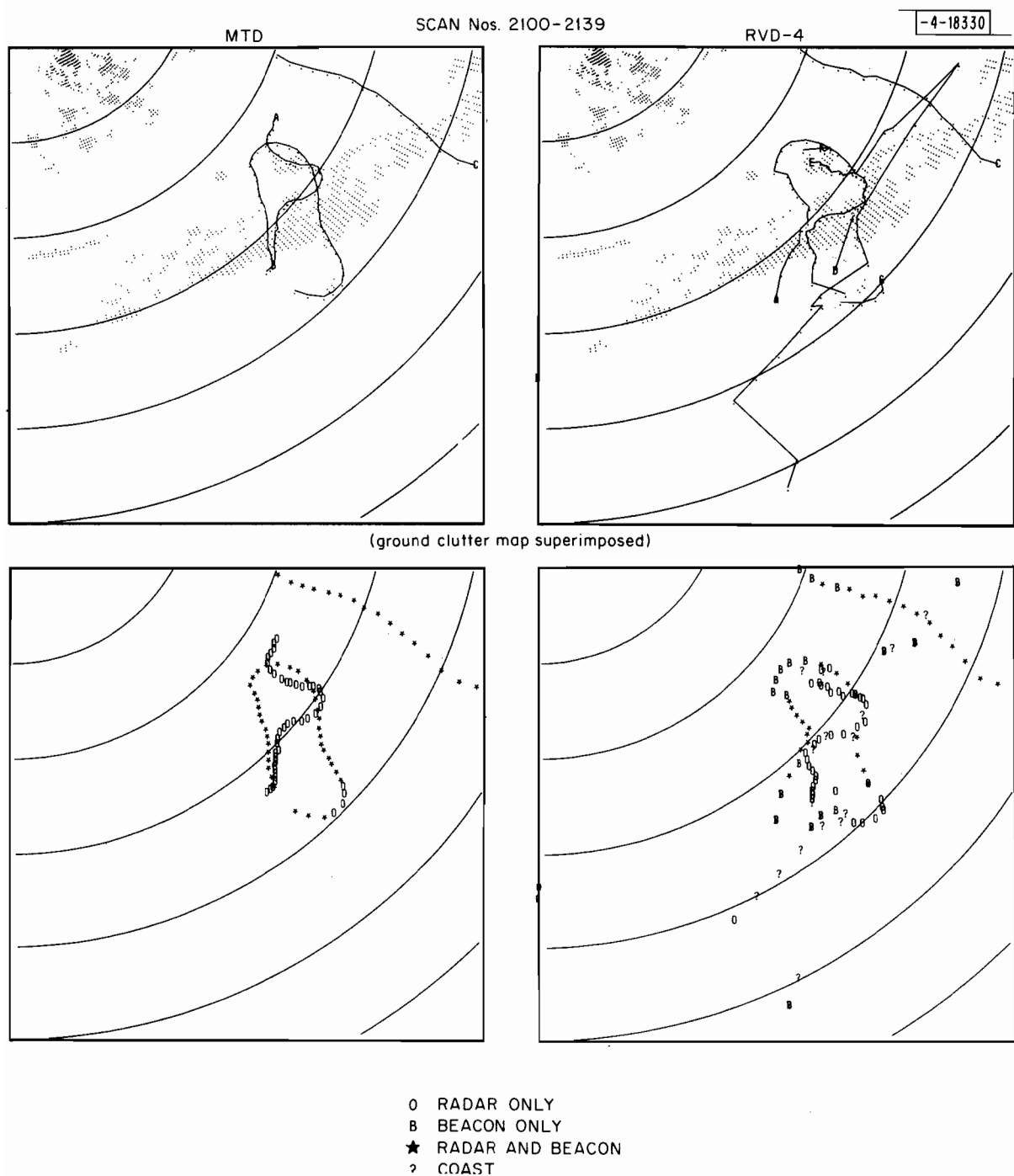


Fig.V-37. MTD vs RVD-4, ARTS-III tracker output in ground clutter.
(Scans 2100-2139, 12 August 1975).

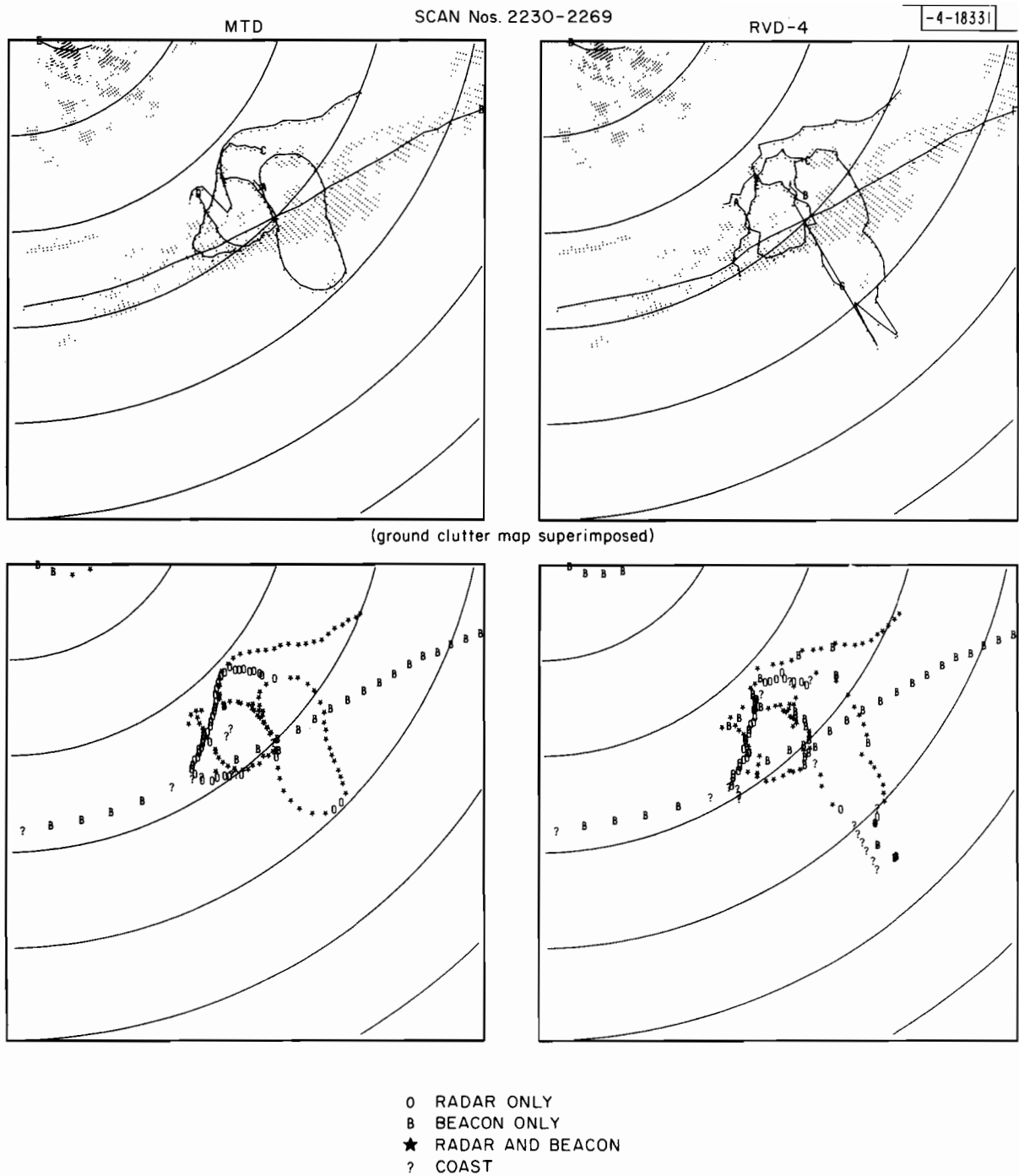
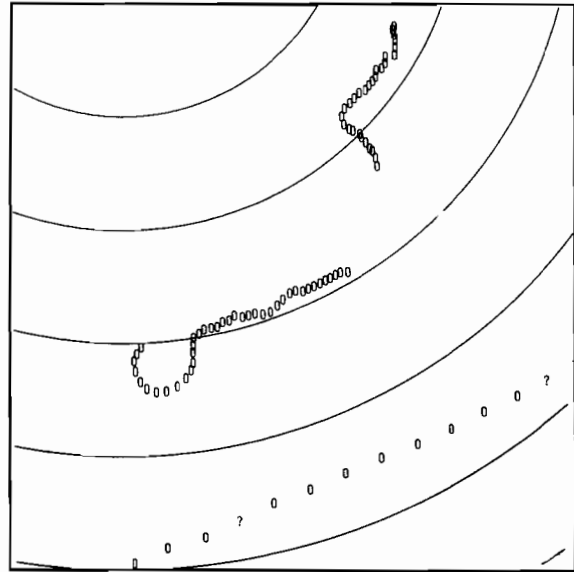
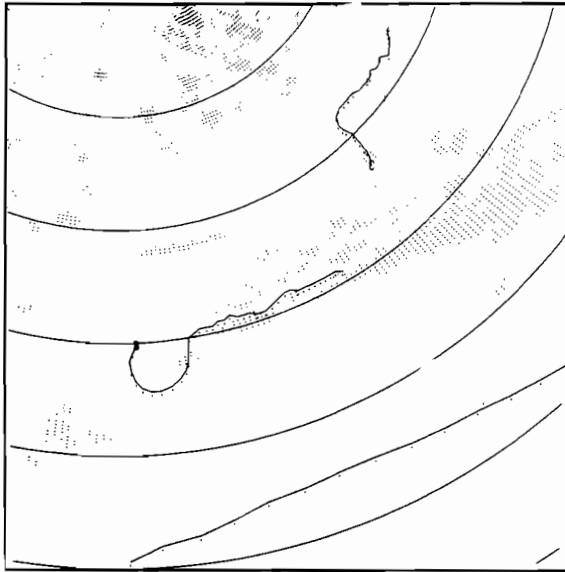


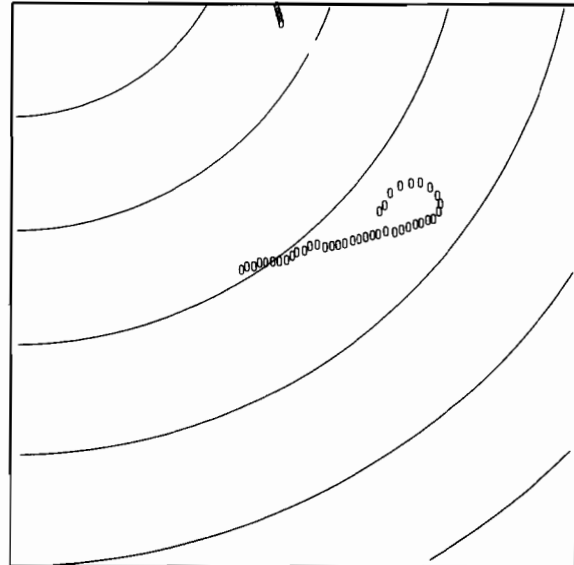
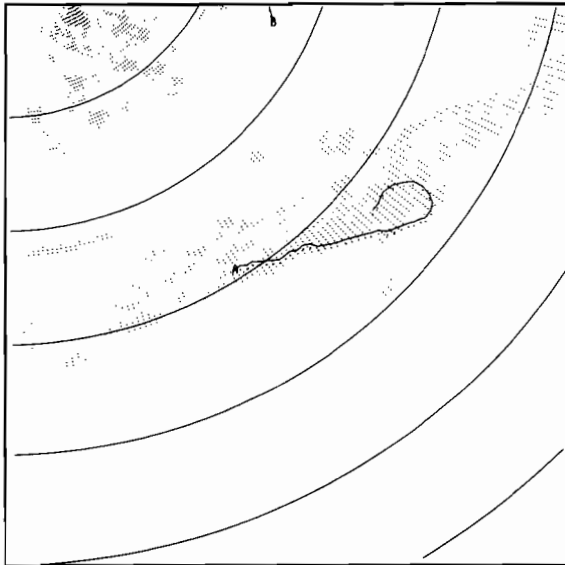
Fig.V-38. MTD vs RVD-4, ARTS-III tracker output in ground clutter.
(Scans 2230-2269, 12 August 1975).

SCAN Nos. 870-909

-4-18332



SCAN Nos. 910-949



(ground clutter map superimposed)

0 RADAR ONLY
? COAST

Fig.V-39. MTD radar-only tracker output in ground clutter.
(Scans 870-909 and 910-949, 12 August 1975).

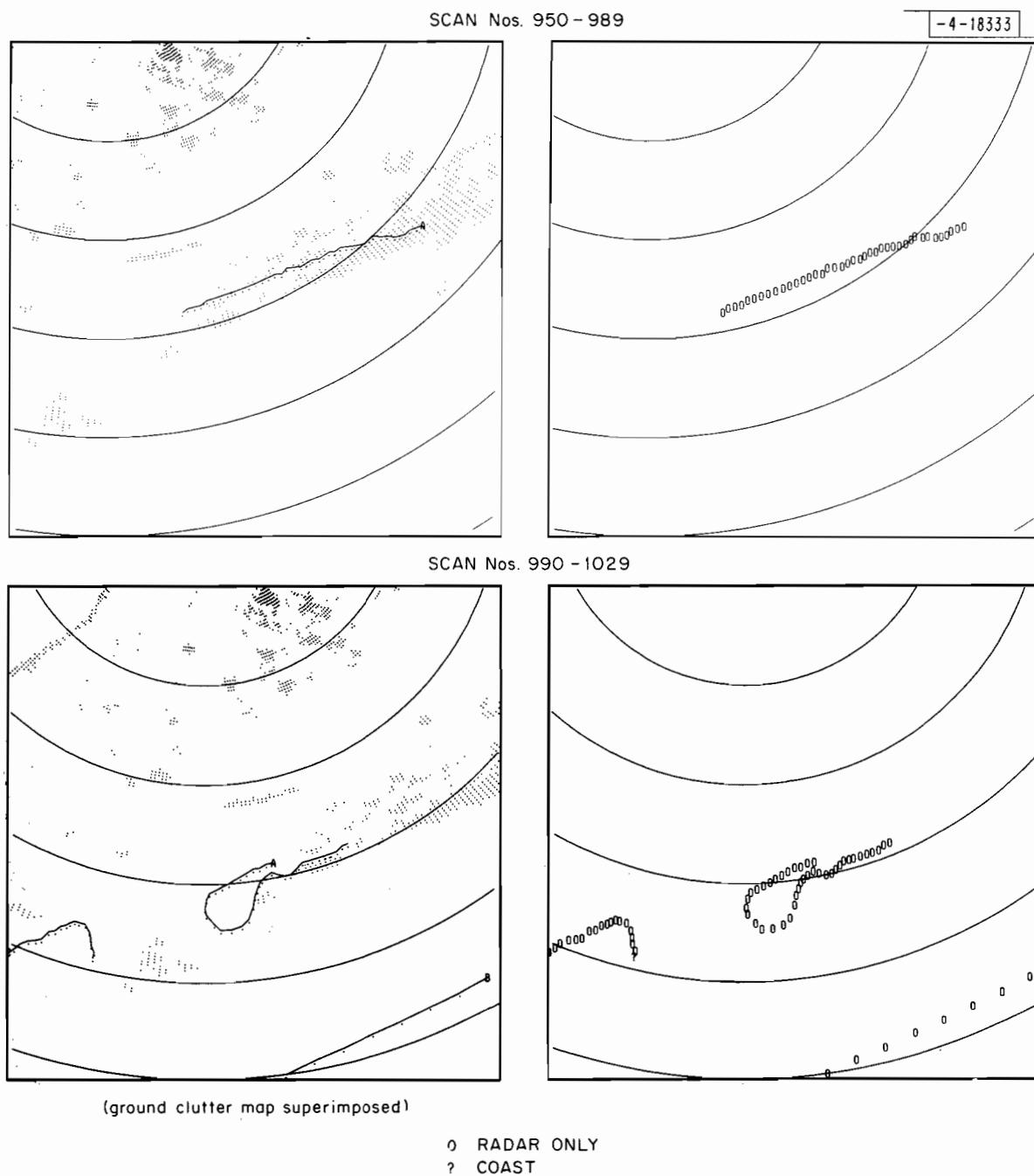
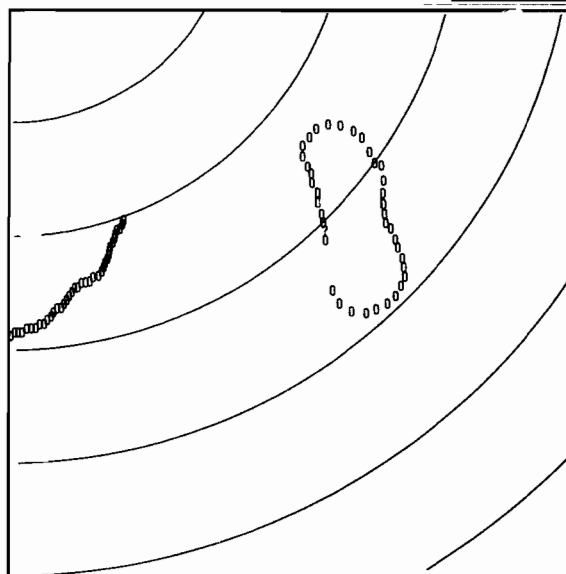
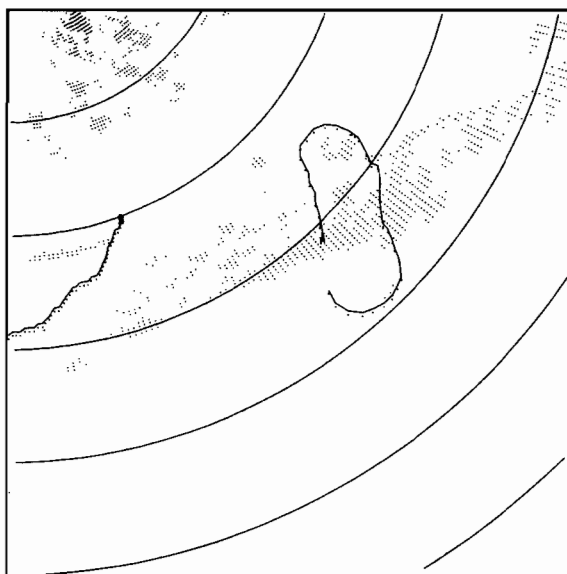


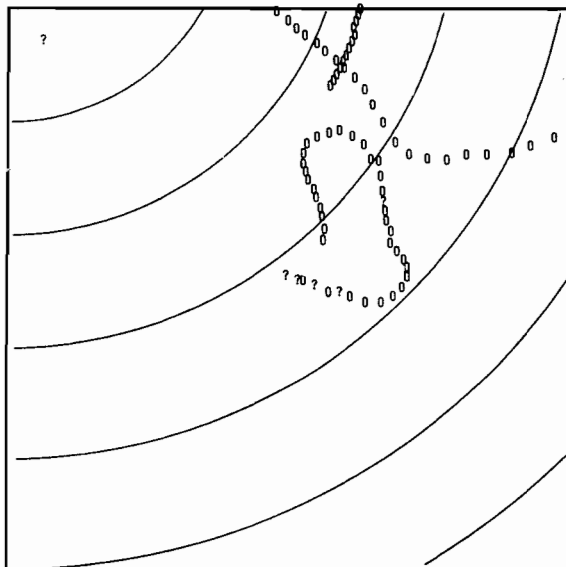
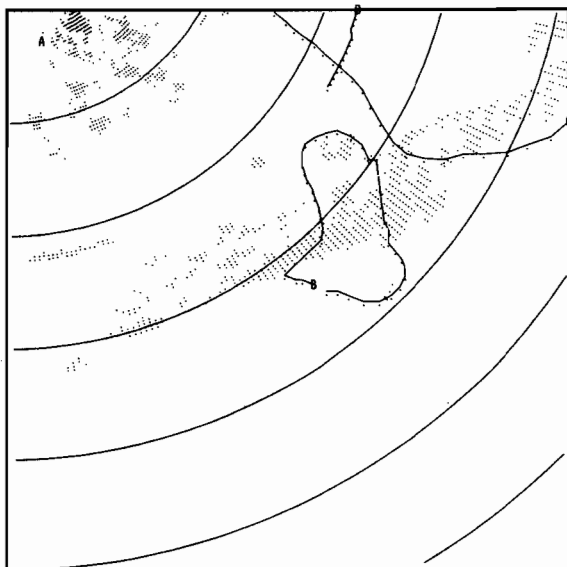
Fig.V-40. MTD radar-only tracker output in ground clutter.
(Scans 950-989 and 990-1029, 12 August 1975).

SCAN Nos. 2021-2059

-4-18334



SCAN Nos. 2060-2099



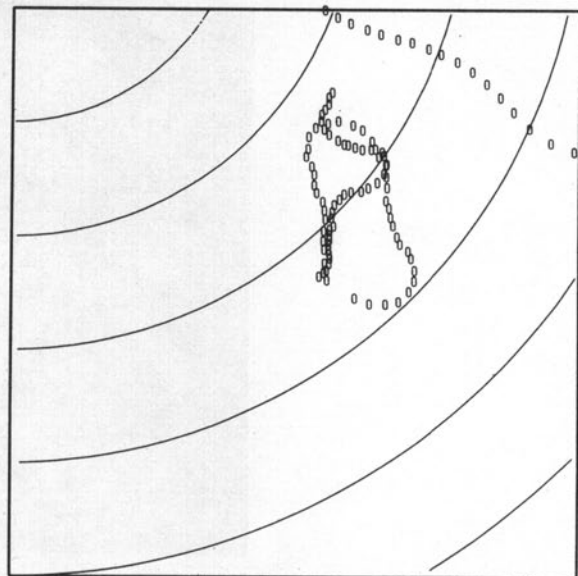
(ground clutter map superimposed)

0 RADAR ONLY
? COAST

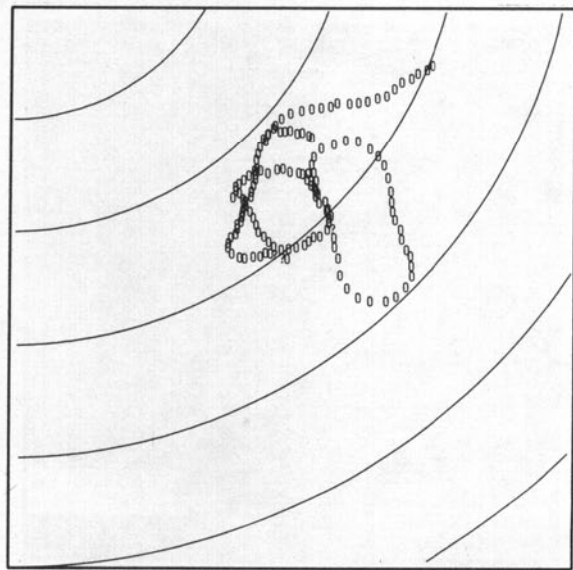
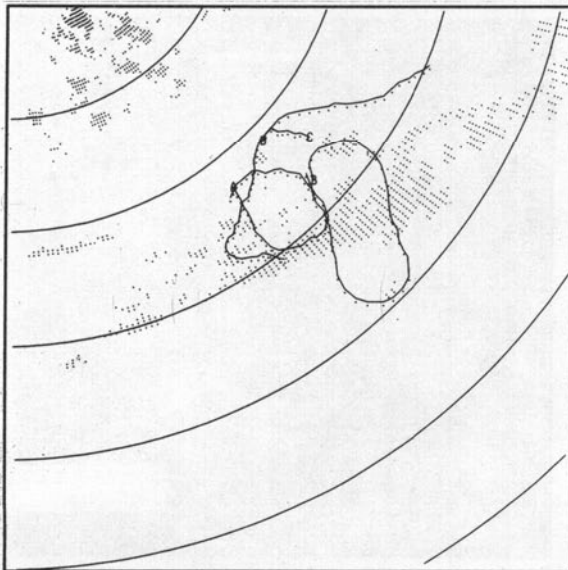
Fig.V-41. MTD radar-only tracker output in ground clutter.
(Scans 2021-2059 and 2060-2099, 12 August 1975).

SCAN Nos. 2100 - 2139

-4-18335



SCAN Nos. 2230 - 2269



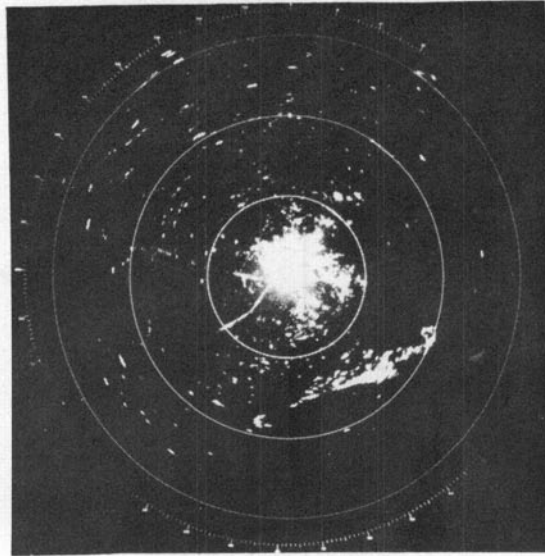
(ground clutter map superimposed)

o RADAR ONLY
? COAST

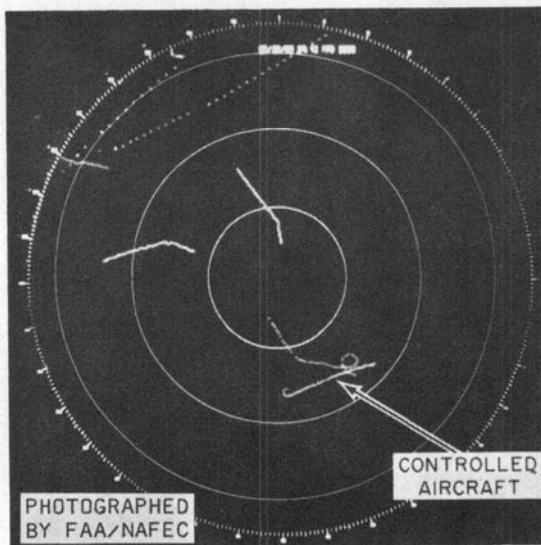
Fig.V-42. MTD radar-only tracker output in ground clutter.
(Scans 2100-2139 and 2230-2269, 12 August 1975).

NORMAL VIDEO

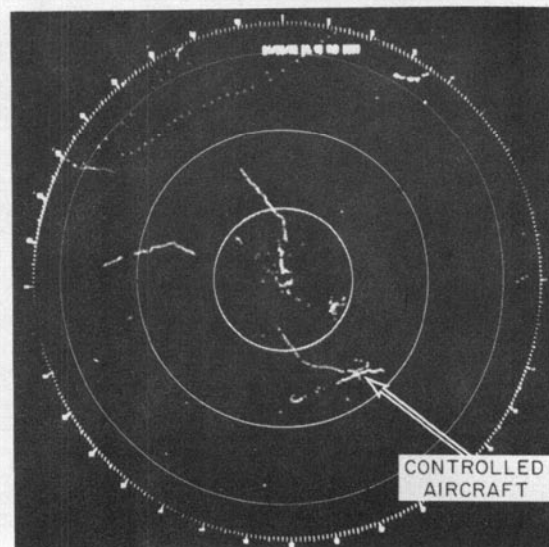
-4-18057



MTD



RVD-4



(5 nmi. Range Rings)

Fig.V-43. MTD vs RVD-4, radar only in ground clutter.

F. Accuracy Studies

The accuracy of the radar report data input to the ARTS-III tracker strongly influences the performance of the tracker. More accurate radar reports will allow the tracker's primary and secondary correlation search bins to be smaller and thus reduce false track initiations. In addition, increased accuracy will allow the tracker to detect aircraft maneuvers sooner. With this in mind, a careful study of the range and azimuth accuracy of the MTD and RVD-4 (sliding window detector) reports and tracks was made. One hundred aircraft targets of opportunity were selected from three clear day tests flown at NAFEC on 12, 21 August and 2 September 1975. These tracks were selected as follows:

- . For 30 successive scans of the radar, at least 27 MTD radar reports, 27 RVD-4 radar reports and 27 beacon reports were successfully correlated and tracked.
- . All tracks chosen were nearly straight or gradual turns (smooth).
- . A variety of track orientations relative to the radar were chosen.

For each selected track, three data types were used:

- . MTD and RVD-4 radar report data after intrascan correlation and interpolation,
- . Beacon report data,
- . Predicted track position data for radar/beacon correlated tracks

For each data type a least squares fit^{*} to a fifth order polynomial was applied independently to the range vs scan number and azimuth vs scan number data.

A measure of the smoothness or random error in a set of data points is given by the root-mean-square deviation of the measured data points from a curve fitted through them. This deviation may be normalized by the number of data points and the number of terms in the polynomial. A computer program was

* A description of the curve fitting techniques used in this analysis is presented in Reference 1.

written to perform the curve fitting and to calculate the deviation. This software was interfaced to the interactive graphics program described in Reference 1. This resulted in an interactive graphics program with which data could be visually scanned and, as appropriate, analyzed for range and/or azimuth accuracy.

Figures V-44 and V-45 present histograms of the deviations in range and azimuth for the three types of sensor report data. The mean deviations are also presented. The MTD, RVD-4, and beacon report data correspond to: beam splitting in azimuth 10 to 1, 7 to 1, and 9 to 1 respectively, and in range, (no interpolation) to a range accuracy of 1/3 range cell, 1/2 range cell and 1/3 range cell respectively. It should be noted that the MTD data is at least as accurate in range and azimuth as the ATCRBS Beacon data. The accuracy analysis was also done for the MTD/Beacon and RVD-4/Beacon tracker output range and azimuth data. The MTD/Beacon data is nearly twice as accurate as the RVD-4/beacon data in both range and azimuth. The results are presented in Figs. V-46 and V-47.

G. Two Target Resolution

In order to compare the ability of the FPS-18/MTD system and the ASR-7/RVD-4 system to detect and track aircraft which are in close temporal and spatial proximity a special set of tests were performed. On 2 September 1975, two controlled aircraft, a Piper Cherokee Arrow and an Aero Commander, flew a two-hour mission near NAFEC. One aircraft flew at an altitude several hundred feet above the other. The Piper Cherokee's course was relatively straight while the Aero Commander flew a crisscross pattern that intercepted the other aircraft's path both temporally and spatially (in range and azimuth). A schematic of their trajectories is shown in Fig. V-48. During the tests the angle with which the two tracks crossed was varied from 0 to 90°. A graph of radar blip-scan ratios for the two aircraft are presented in Figs. V-49 and V-50 for both the MTD and RVD-4.

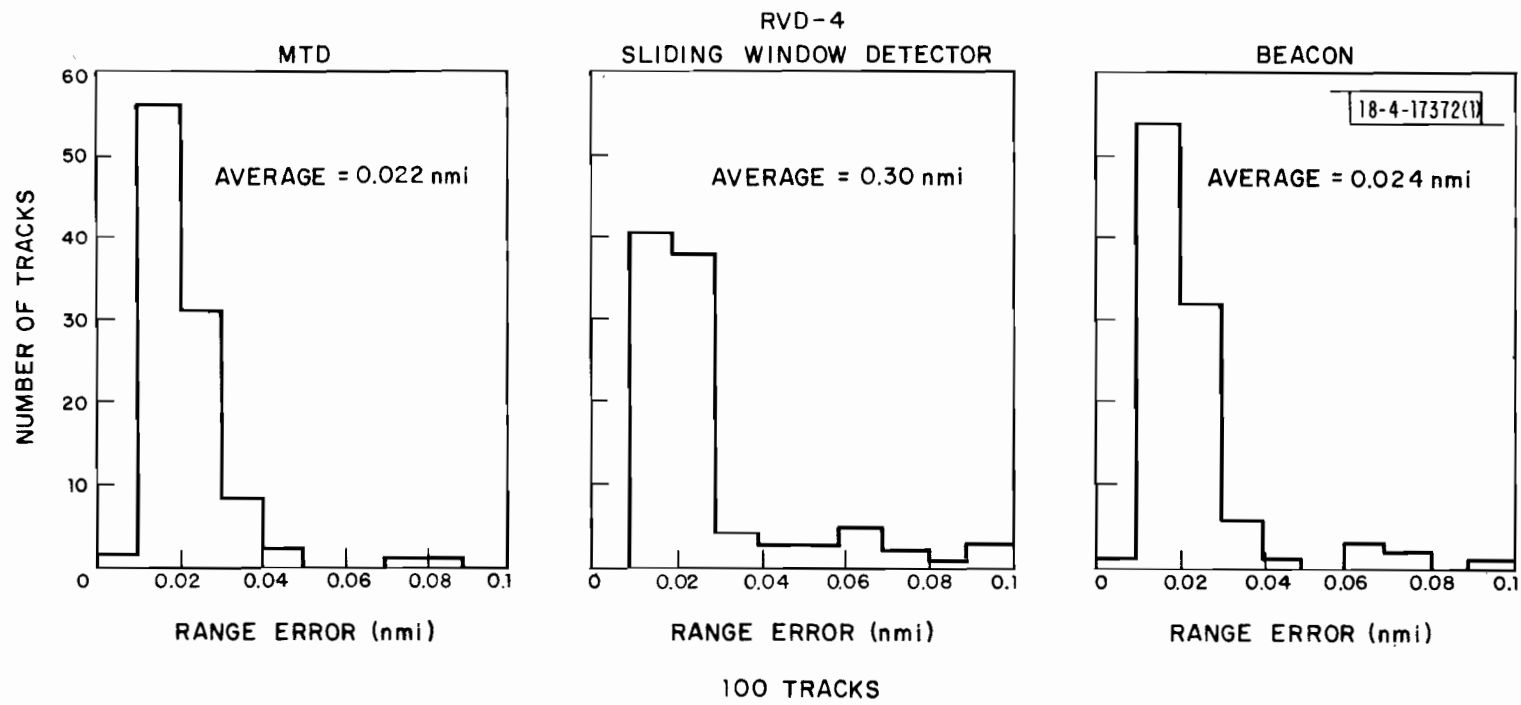


Fig.V-44. MTD vs sliding window detector vs beacon report data range error.

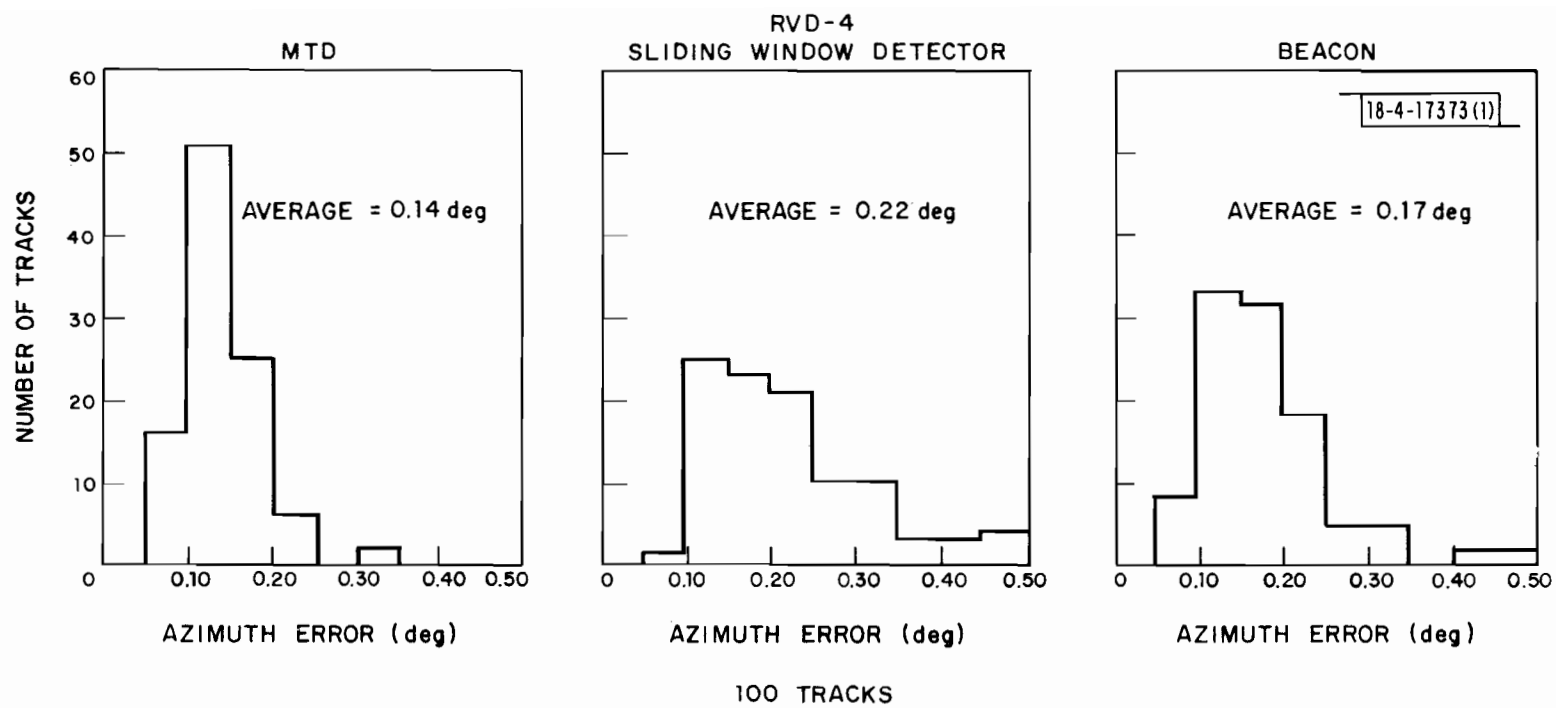


Fig.V-45. MTD vs sliding window detector vs beacon report data range error.

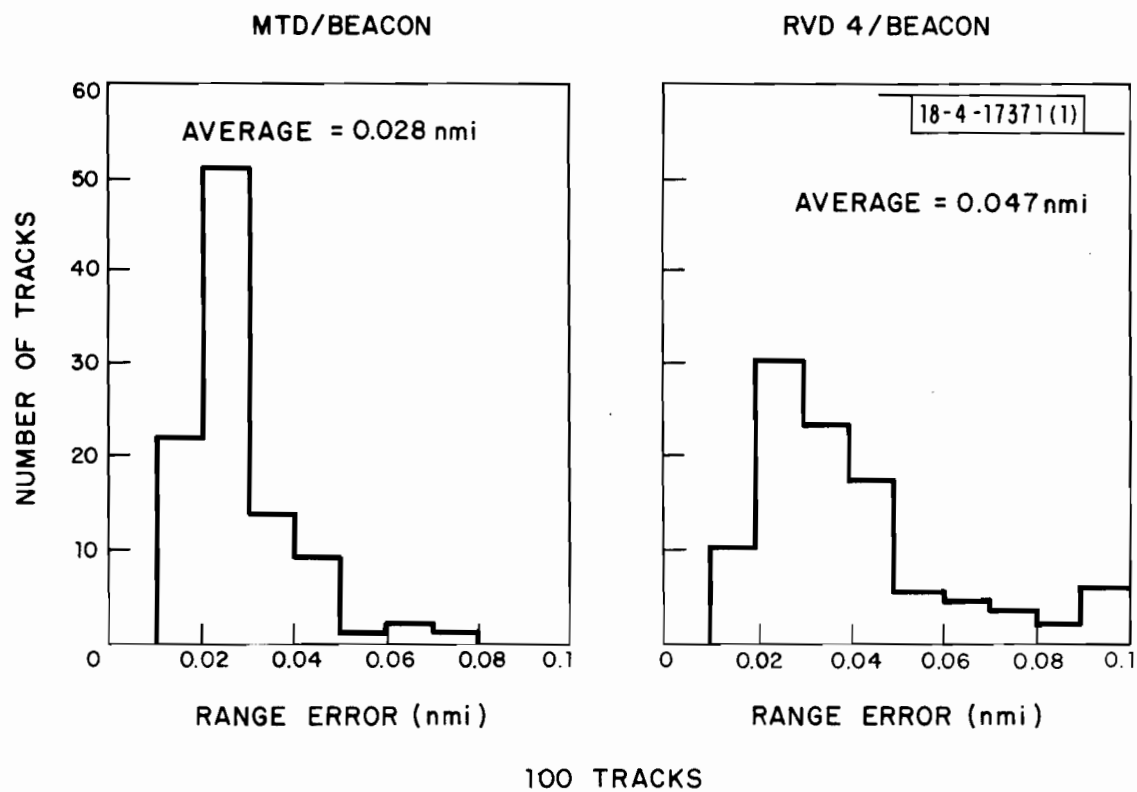


Fig.V-46. MTD vs RVD-4, beacon track data range error.

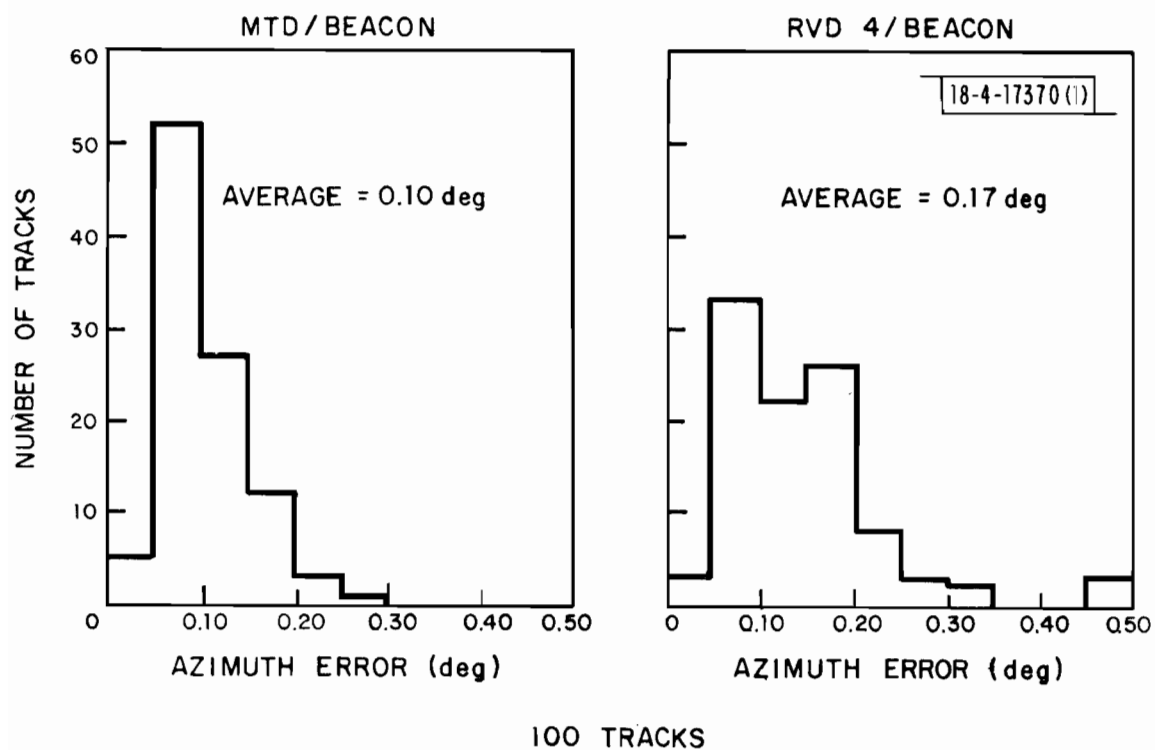


Fig.V-47. MTD vs RVD-4, beacon track data azimuth error.

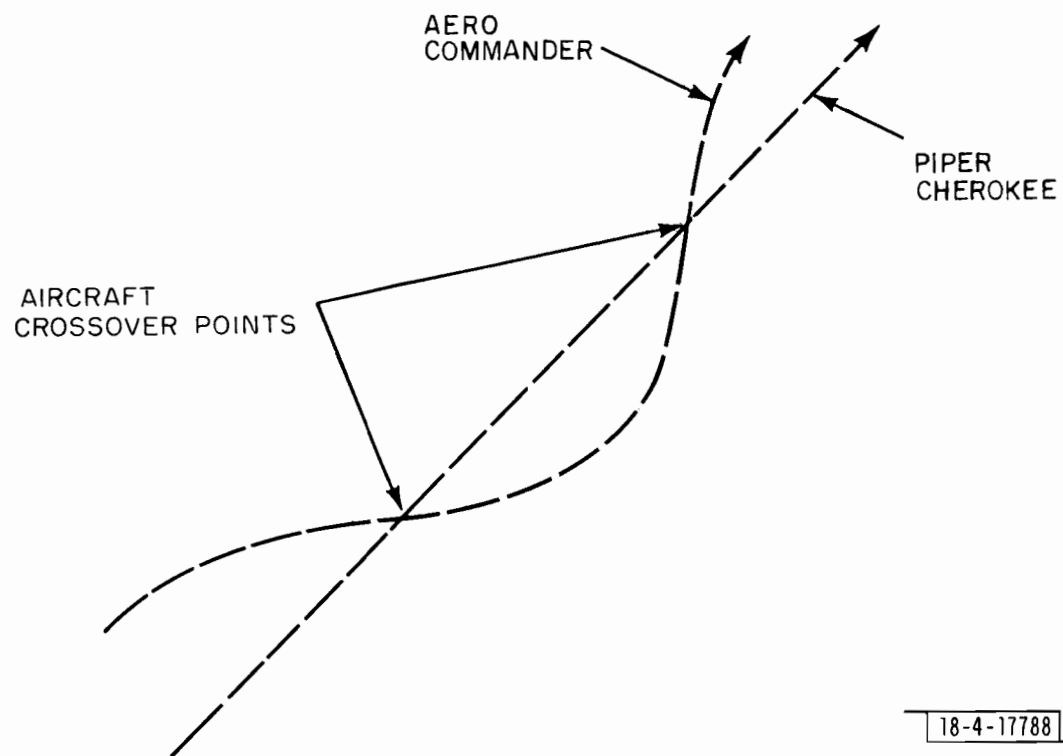


Fig.V-48. Crossing flight paths: test flight of 2 September 1975.

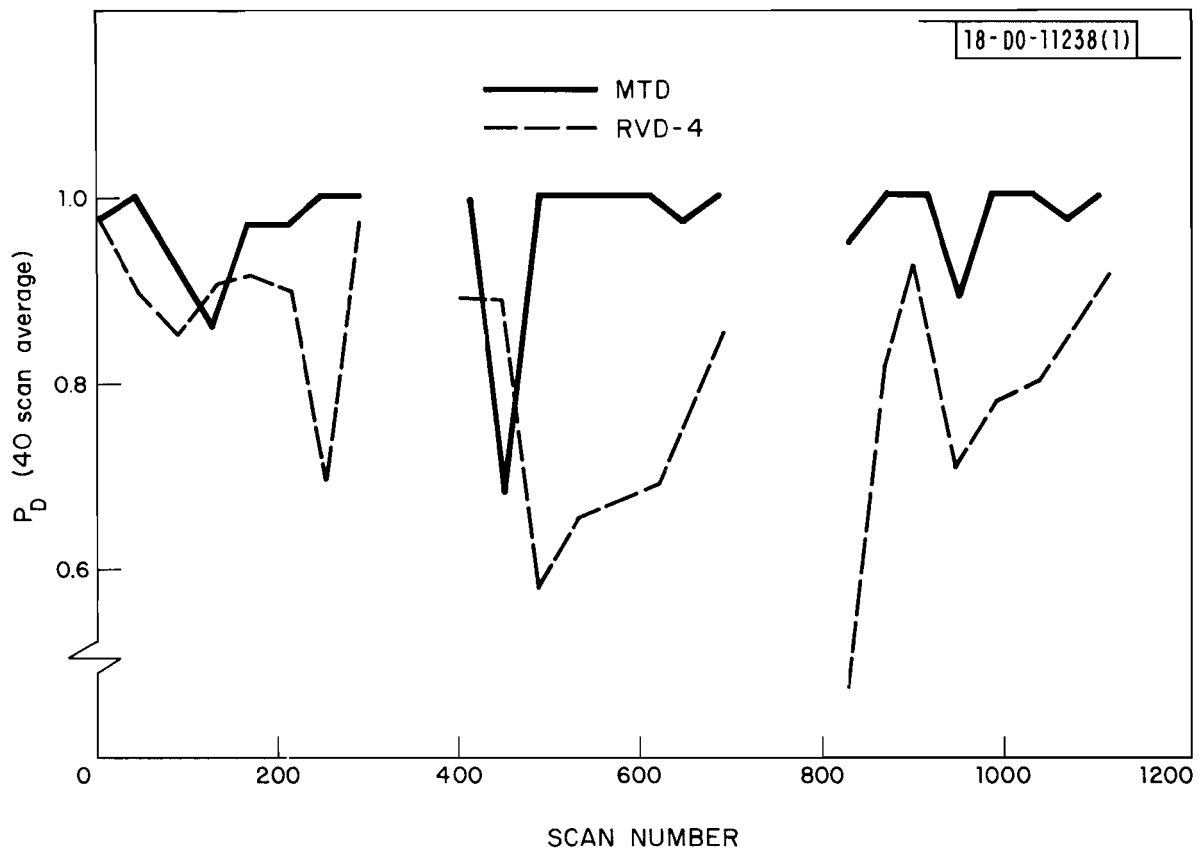


Fig.V-49. Blip/scan ratio for test flight of 2 September 1975.
(Aero Commander).

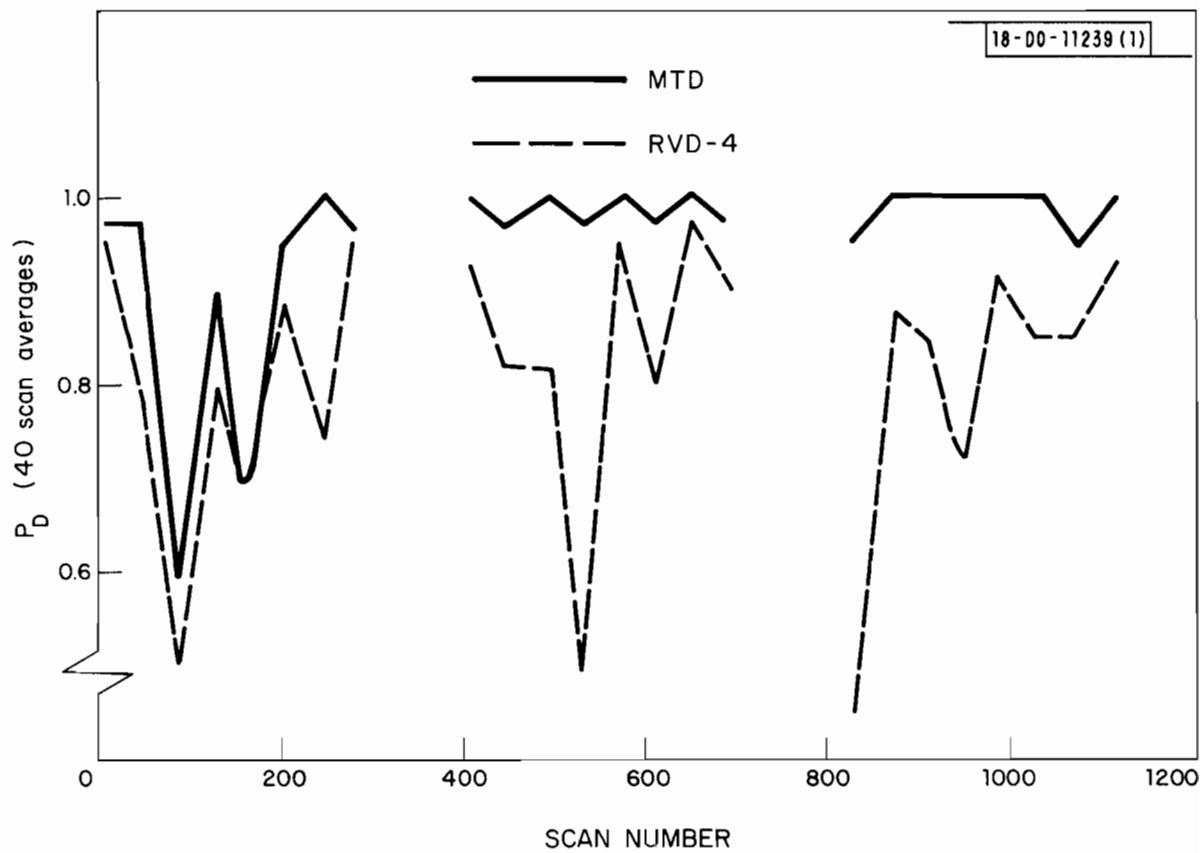


Fig.V-50. Blip/scan ratio for test flight of 2 September 1975.
(Piper Cherokee).

The average blip scan ratios for the test are presented in Table V-1.

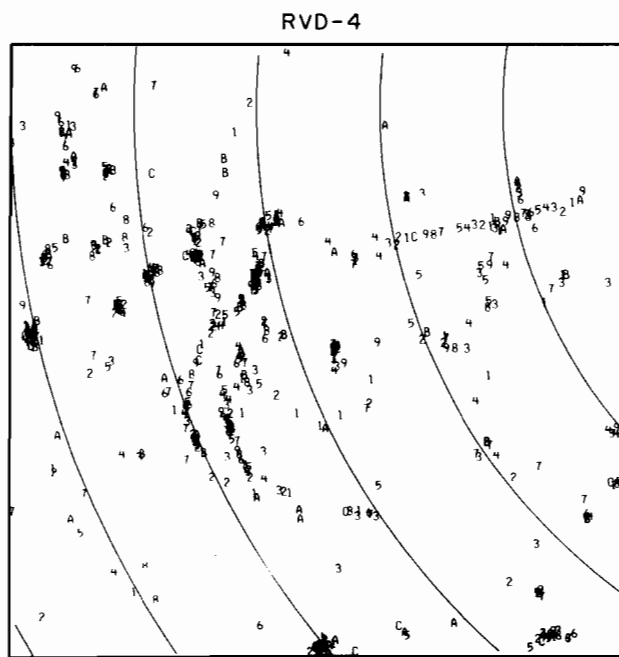
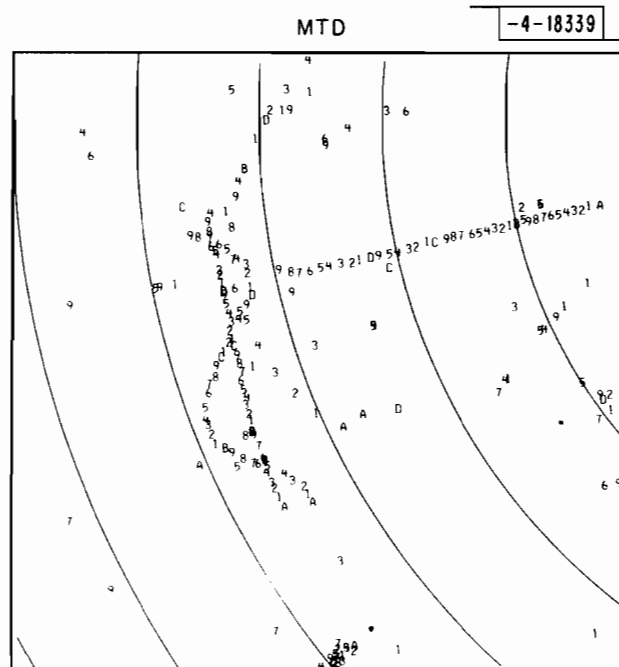
TABLE V-1
AVERAGE BLIP SCAN RATIOS OF RADAR REPORTS

	<u>MTD</u>	<u>RVD-4</u>
Aero Commander	0.965	0.80
Piper Cherokee	0.95	0.81

Examples of the detection performance of the MTD and RVD-4 at the radar report level are presented in Fig. V-51. Note that the controlled aircraft cross each other three times. In each case the aircraft are unresolved for a few radar scans.

Next, radar-plus-beacon report data was processed through the ARTS-III tracker and the results were examined. Figures V-52 and V-53 presents forty scans of MTD and RVD-4 automated tracker output for the radar-plus-beacon and radar-only data which corresponds to Fig. V-51.

The greater accuracy of the MTD report data relative to the RVD-4 data causes the improved tracker performance in the MTD case. The radar-only tracking results for both the MTD and RVD-4 are poor whenever the ARTS-III tracker has two tracks whose track windows overlap and thus cause both reports from both tracks to fall into "both track" windows. The ARTS-III tracker then gives up and coasts even when the correct choice of reports with tracks is obvious. This tracker deficiency will be remedied when using the MTD data since the data is more accurate and since radial velocity and strength information will be used to resolve the ambiguities (see Fig. V-51). The tracking performance, with beacon data added, is improved greatly because the beacon codes of each beacon report are used by the tracker to correlate the report with an already established track.



SCANS 950-989

Fig.V-51. MTD/RVD-4, radar reports. (Scans 950-989, 2 September 1975).

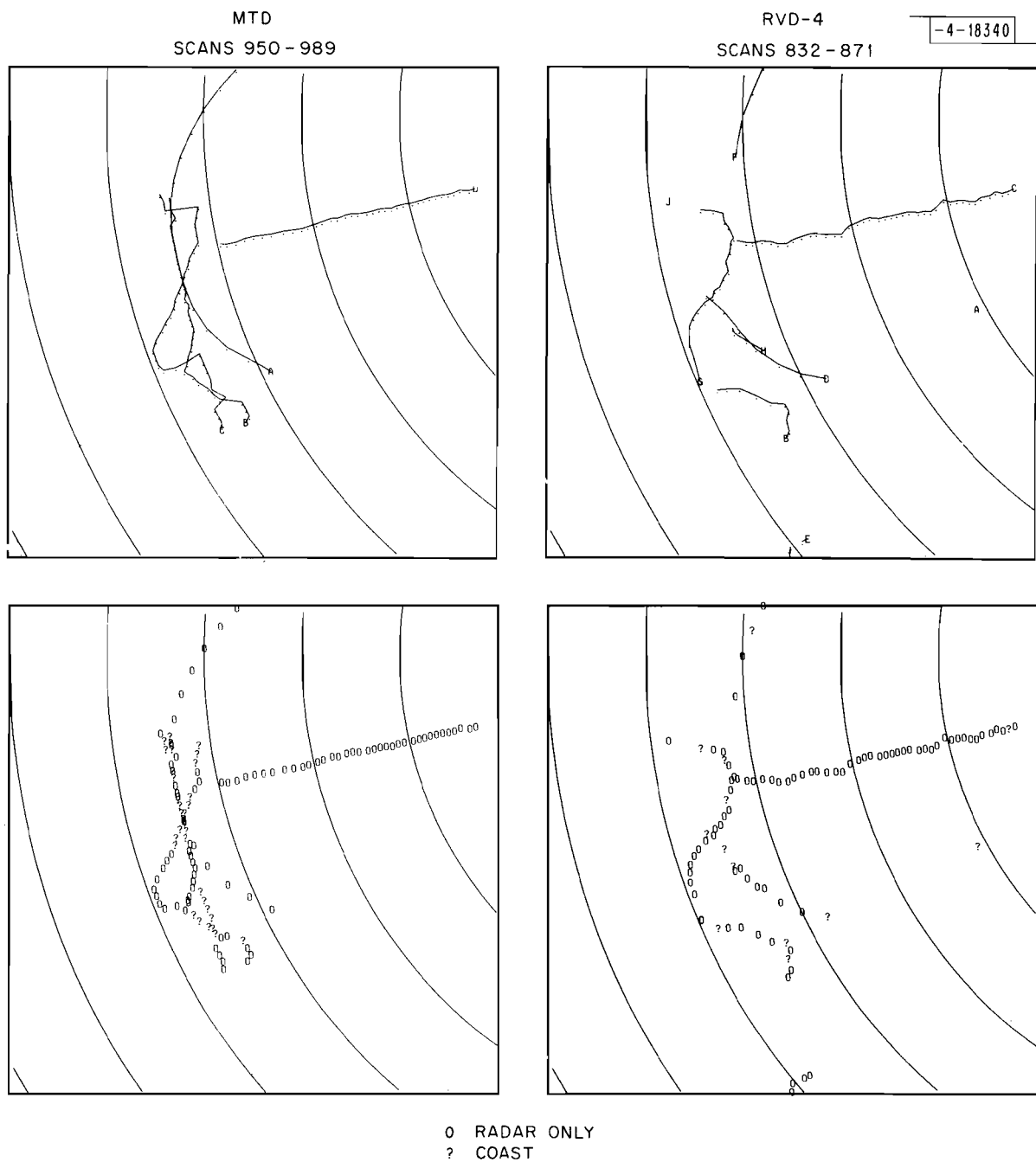


Fig.V-52. MTD/RVD-4, tracker performance, radar only. (2 September 1975).

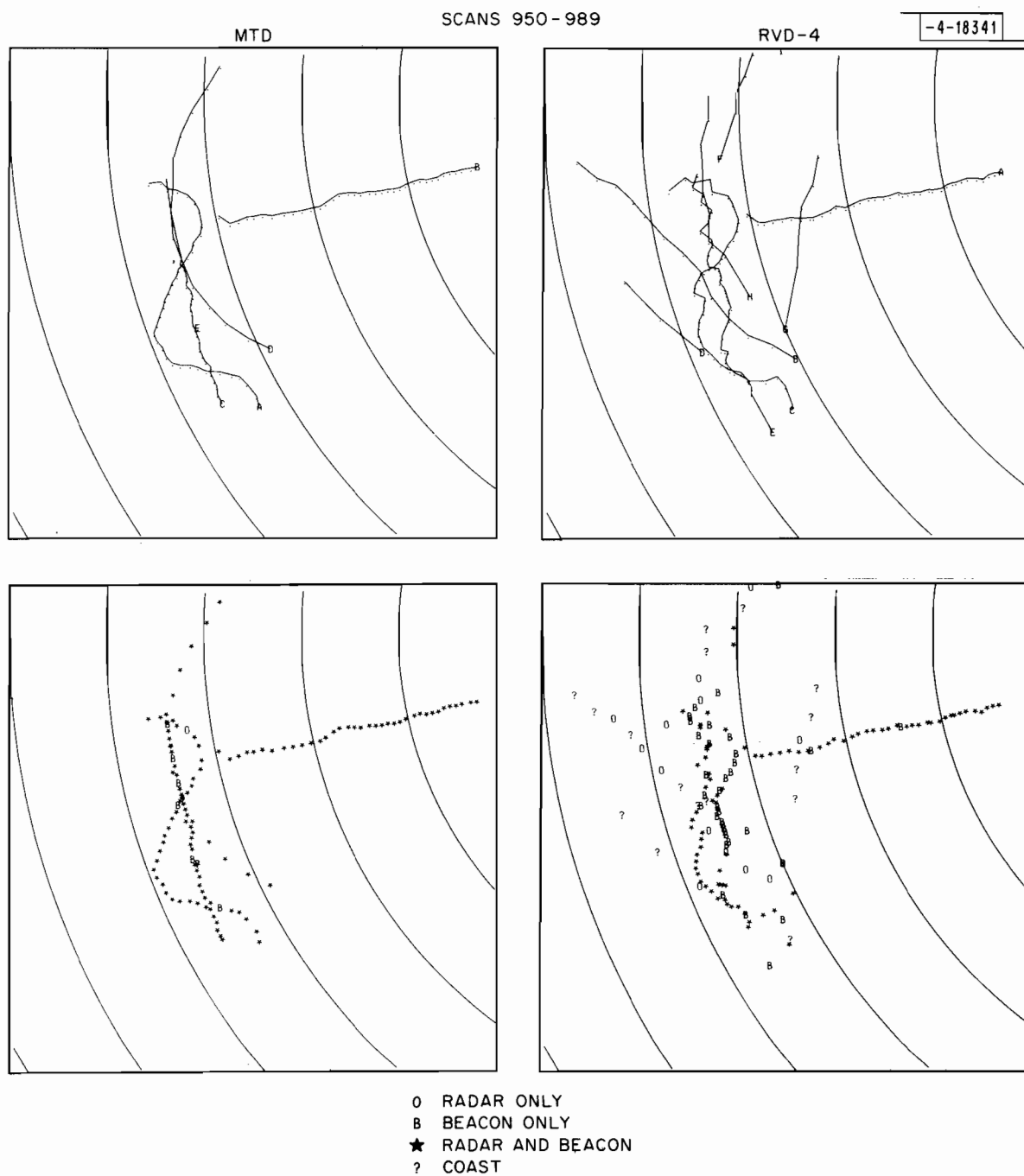


Fig.V-53. MTD/RVD-4, tracker performance. (Scans 950-989, 2 September 1975).

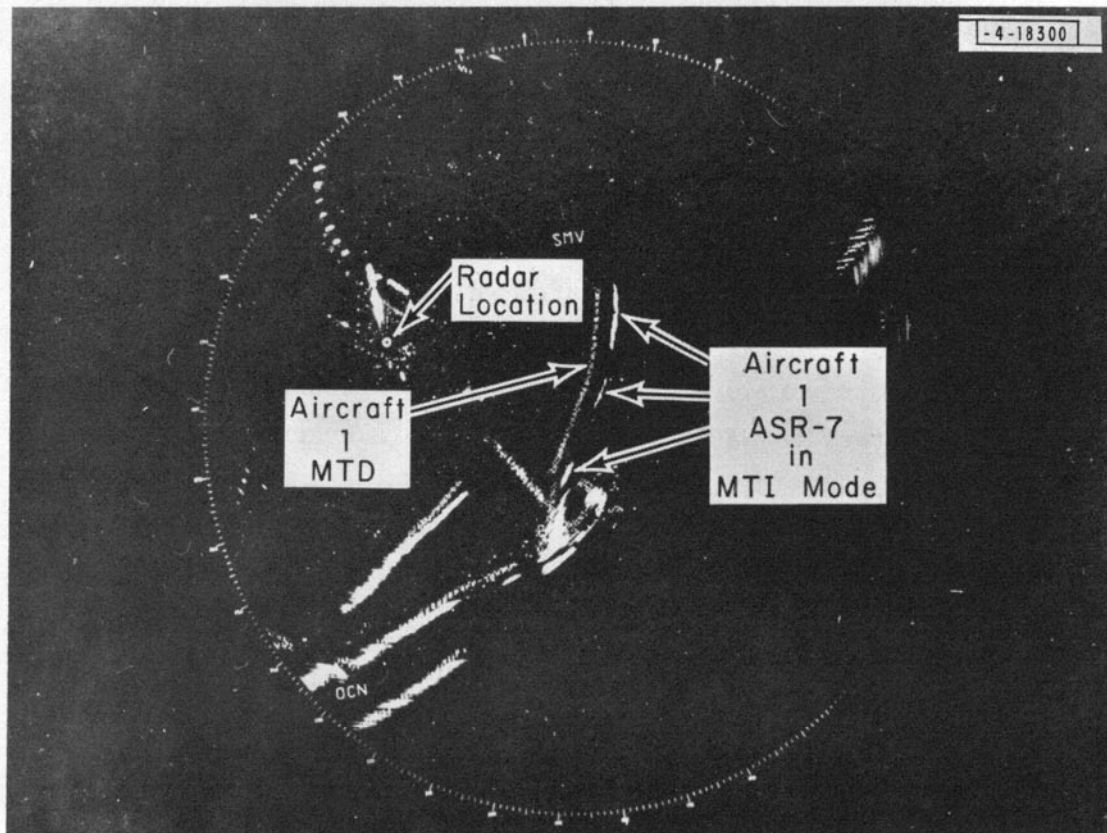
H. Tangential Aircraft Detection Performance

For an automated radar tracking system to perform reliably, missed radar detections must be completely spatially uncorrelated from scan-to-scan of the radar. One way that correlated missed radar detections can occur is when a conventional ASR radar is operated in the MTI mode. Under these conditions the goal of the MTI canceller is to reject correlated returns (ground clutter) from the radar. This of course causes poor detection of tangentially moving aircraft since they are characterized by low or zero radial velocity. The effect of the MTI mode on tangentially flying aircraft is shown in Fig. V-54. Here output from the ASR-7 in the MTI mode is compared with the output from the MTD. The RVD-4 attempts to alleviate this problem by choosing the normal video or MTI video channel for processing depending on whether or not clutter is present. Unfortunately, the size of the smallest area which is switched between channels is 2.8° in azimuth by 2 nmi in range. With such a large cell, a single large clutter return can cause the entire 2.8° by 2 nmi area to be in the MTI mode and thus have poor low velocity response.

No test flights were made with the main purpose of testing the MTD and RVD-4 tangential aircraft detection performance. However, most of the test flights contain data for situations in which the controlled aircraft were flying tangentially. Analysis of these test flights shows that the MTD had excellent detection performance when the aircraft were flying tangentially whether the aircraft was in rain or ground clutter. Data analysis also showed that the RVD-4 suffered many correlated radar dropouts when the test aircraft were flying tangentially near regions of ground or rain clutter. These missed detections caused poor tracking performance in regions of clutter. Examples of these effects are presented in Sections V-C and V-E.

I. Conclusions

While both processors exhibited adequate detection and false-alarm performance in the clear, the detection and false alarm performance of the MTD was far superior to that of the RVD-4 in rain and ground clutter. MTD processed radar reports were significantly more accurate than RVD-4 radar reports, and the MTD did not suffer from track dropouts while tracking tangentially flying aircraft, as did the RVD-4.



THIS LONG EXPOSURE PHOTOGRAPH SHOWS THE RELATIVE PERFORMANCE OF THE FPS-18/MTD SYSTEM AND THE ASR-7 IN THE MTI MODE. THE TWO RADARS ARE CO-LOCATED IN THE UPPER LEFT PORTION OF THE DISPLAY. THE OUTPUT OF THE TWO RADARS IS SLIGHTLY OFFSET ON THE PPI TO FACILITATE EXAMINATION OF THE TRACKS. THE MTD PROCESSOR CLEARLY DETECTS THE TANGENTIALLY FLYING AIRCRAFT (MARKED 1), WHILE THE TRACK FROM THE ASR-7 IN THE MTI MODE CONTAINS LONG GAPS WHEN THE AIRCRAFT IS IN THE ZERO RADIAL VELOCITY NOTCH OF THE MTI CIRCUIT. SINCE THE RVD OPERATES ON THE MTI VIDEO DATA IT CANNOT PERFORM BETTER THAN THE DATA PROVIDED TO IT BY RADAR.

Fig.V-54. Comparison of MTD with ASR-7 in MTI mode.

ACKNOWLEDGEMENTS

The development and testing of the MTD system took more than two years and benefited from the contributions of a large number of people in several different organizations. A sincere effort has been made to acknowledge all significant contributions to this project.

The MTD processor was developed in Lincoln Laboratory's Radar Techniques Group. In addition to C. E. Muehe who is the Group Leader, M. Labitt and P. B. McCorison contributed to the system design while W. H. Drury was responsible for most of the MTD's digital design. The construction of the MTD, the modification of the FPS-18 radar, system integration and transportation of the MTD from Lincoln Laboratory to NAFEC were made possible by the enthusiastic efforts of a number of Lincoln Laboratory personnel including W. Crowder, A. J. Dioron, H. P. McCabe, R. P. Meuse, M. A. Nader, C-S. Lin and G. P. Gagnon contributed to the design and construction of the NOVA computer subsystem. R. D. Lewis and C. M. Hardy of Lincoln Laboratory and C. Hayes of ARCON, Inc. developed most of the software used in the NOVA and in the non-real-time data analyses. Also, the constructive direction of H. G. Weiss and P. R. Drouilhet was appreciated.

We also want to thank Messrs. K. Coonley, D. Hopson and D. Turnbull of the FAA/Research and Development for their continuing support.

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We wish to acknowledge the work of R. Johnson, K. Tschetter and L. Vogel of Univac who designed and produced the ARTS-III software portions of the MTD system.

Finally, we acknowledge with thanks the hours spent by A. L. Smith and L. J. Wesley in the preparation of this manuscript.

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