ADVANCED SIGNAL PROCESSING FOR AIRPORT SURVEILLANCE RADARS*

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ABSTRACT

The inclusion of airport surveillance radars (ASR) in an automated air traffic control system, such as the ARTS-III, has been limited by the present radar's capability to automatically reject ground clutter, weather clutter and angels while still maintaining good detectability on all aircraft within their coverage patterns. Analytical and experimental studies have been performed which indicate that new techniques[1] can significantly enhance the automated capability of these radars. A special-purpose, hard-wired, digital signal processor has been designed, built and tested which provides near-optimum target detection over the entire ASR coverage out to 48 nmi. The processor which coherently integrates eight pulses has both a fine grained clutter map for optimal thresholding in high ground clutter environments and a mean-level thresholding scheme for filtering those Doppler cells which contain heavy precipitation. Because of the processor's ability to detect targets in a high ground clutter environment, the ASR's will be able to operate their antennas at lower elevation angles and, thus, have better coverage of low flying aircraft near the terminal. The processor is initially being tested on a highly modified, coherent S-band, FPS-18 radar. The stability of the klystron transmitter was improved so that it would not limit system performance and a new, wide dynamic range, linear receiver was provided.

I. PROBLEM DESCRIPTION

Automated airport surveillance radars must exhibit simultaneously low false alarm rates and high probabilities of detection of aircraft in the presence of extraneous clutter reflections. Three types of interfering clutter have been found to predominate: ground clutter, weather clutter and angels.

The ground clutter radar backscatter coefficient varies appreciably from spot to spot in the area of coverage. The present ASR radars suppress ground clutter by three mechanisms: MTI, antenna tilt and by mounting the antenna close to the ground to take advantage of the shielding effect of nearby objects. The MTI processors in these radars employ limiting in the IF, followed by a phase detector. The purpose of the limiting is to normalize the video output so that clutter residue from the MTI filter is reduced to the average noise level. This limiting action spreads the clutter spectrum so that considerably poorer subclutter visibility (SCV) is achieved that if the normalization had been done by some other mechanism not involving nonlinearities. The performance of S-band, three-pulse cancellers with and without limiting is presented in Figure 1. In order to obtain reasonable signal-to-clutter ratios, it is commonplace for the present ASR's to tilt the antenna upward by 2 to 5 degrees depending on the local clutter situation. This advantage is offset by the degraded detectability of aircraft flying at low elevation angles.

In the so-called "second-time-around" clutter effect, returns are being received due to illumination of clutter beyond the nonambiguous range by the next-to-last pulse transmitted. These returns are prevalent where conditions for anomalous propagation exist or in regions where mountains exist beyond the nonambiguous range. Present ASR's use magnetron transmitters that transmit pulses with random phase from pulse to pulse. Thus, it is impossible to maintain the phase relation between the first and second-time-around clutter returns and the two cannot be filtered out simultaneously.

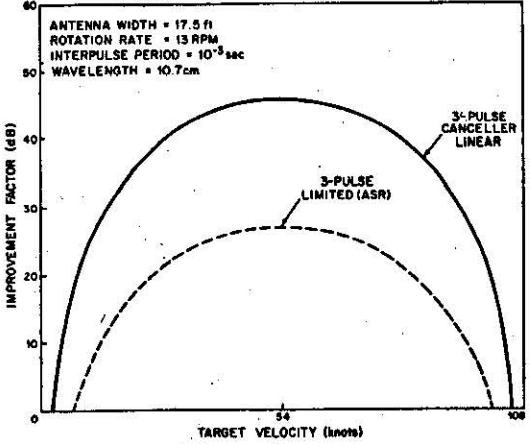

Figure 1

Performance of S-Band 3-Pulse Cancellers. The improvement factor is the ratio of signal-to-clutter out of the canceller to signal-to-clutter in. The latter ASR radars use 3-pulse cancellers following a limiter shown above by the curve "3-pulse limited (ASR)"

The backscatter from precipitation has been studied extensively[2, 3, 4]. Circular polarization is normally used to reduce rain clutter by about 15 dB while reducing the signal level to some extent. The use of MTI helps reduce rain clutter except when the antenna is looking toward or away from the wind direction. In these directions the rain clutter spectrum is such that all of the rain clutter

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signals may pass through the MTI filters. Log-FTC-antilog circuits[3,4] reduce the receiver gain in proportion to the average level of rain clutter for about a mile in range surrounding the cell of interest. It, thus, normalizes the rain clutter level just as limiting is used to normalize ground clutter at the output of the MTI circuit. Its purpose is to suppress the rain clutter on the scope. At the same time, of course, it suppresses the signal. For adequate detection, the signal amplitude must be appreciably above the clutter residue from the MTI filters.

So-called "angel clutter" refers to all returns which cannot be explained as being ground or precipitation clutter or targets. Much effort has been spent studying angels. It is now believed that most, if not all, angels are caused by bird flocks[6,7]. Swarms of insects[5] and returns from well organized layers of turbulent refractivity in the atmosphere[6] are two other sources which have been considered possible causes of some angels. Birds fly between 15 and 45 knots true air speed. Taking into account winds, radial velocities over the range ± 80 knots or so may be observed. A fairly effective radar improvement used against bird clutter is a carefully tailored sensitivity time control (STC)[7]. The STC varies the radar gain with range and is adjusted so that the minimum detectable target is a specific value, say, one m^2. This calls for an R^{-4} attenuation law. Some modification of this law may be required to handle ground clutter.

II. SOLUTION

A. Optimum Processing

In order to assess quantitatively what could be considered a "good" MTI processor for improving the performance of ASR radars against fixed ground clutter, calculations were made of the performance of the so-called "optimum processor"[1]. Given the initial conditions, the optimum processor has the highest target-to-interference (interference is defined as clutter plus front-end noise) ratio improvement of any processor. By knowing the performance of such a processor, one can judge how well a conventional, easily implemented or any other processor (i.e., suboptimum) can approach the theoretical limit[8]. The clutter spectrum which in this case is essentially all caused by the antenna scanning motion, is modeled by an antenna having a Gaussian beam shape as in Emerson[9].

Figure 2 shows the target-to-interference improvement in decibels that is possible (optimum) for the mechanically rotating antenna. The results in this section assume the use of a sufficiently stable, coherent transmitter. Poorer results will be obtained using a magnetron transmitter. The parameters are (similar in most respects to the ASR-7):

Antenna Width	5.25 meters
Antenna Rotational Speed	1.36 radians/sec
Wavelength	0.107 meter
PRF	1000 pulses/sec
No. of Pulses Processed/Look	10
Clutter-to-noise Ratio	40 dB

The maximum improvement factor shown in Figure 2 equals the clutter-to-noise ratio assumed (40 dB) times the number of pulses coherently integrated[8].

The maximum clutter-to-noise ratio which can be handled will be set by the dynamic range of available analog-to-digital (A/D) converters. Mean clutter-to-noise ratios of 40 to 50 dB can be handled in available A/D converters with adequate sampling rates.

The upper curve in Figure 2 is the improvement obtained when the optimum filter is tuned to the Doppler frequency of the target as the target Doppler is varied. The lower curve represents the frequency response of the particular optimum filter tuned to 300 Hz.

By comparing these results with those of Figure 1, we see that the amount of clutter rejection achieved in the present radars as well as other conventional MTI systems is far less than the best that can be done.

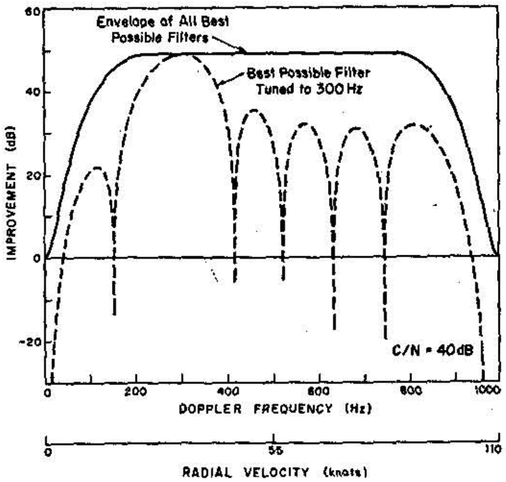


Figure 2

Improvement of Target-to-Interference Ratio, Scanning Antenna

B. Implementation of a Near-Optimum Processor

The optimum processor can be broken into two parts; a clutter filter followed by a target filter. The filter used to reduce clutter multiplies the signal vector by the antenna weighting and by the inverse of the interference covariance matrix. The optimum target filter used to enhance the target is a Discrete Fourier Transform (digital filter bank). The near-optimum processor consists of a three-pulse canceller without feedback which closely approximates the frequency response of the clutter filter followed by a Discrete Fourier Transform for the target filter. This combination gives improvement factors within a few dB of the optimum shown in Figure 2 and requires many fewer multiplications per second.

C. Thresholding

The near-optimum ground clutter processor would not be complete without adequate thresholding. For a typical ASR utilizing a near-optimum processor, ground clutter will appear only in the zero Doppler filter and the filters immediately adjacent on each side. Ground clutter is very spotty in character. It varies greatly in size from one resolution cell to the next. Thus, averaging nearby cells will not give a good estimate for thresholding purposes.

A practical way to accurately set ground clutter thresholds is to use a digital ground clutter map which remembers the ground clutter in every range-azimuth resolution cell averaged over a sufficient time period (number of scans). Whenever an aircraft's cross section is sufficiently larger than the clutter over which it is flying, it will be seen even if it has zero velocity (tangential target).

It is fortunate that the optimum or near-optimum filtering against ground clutter utilizes a filter bank since this is a good approach to eliminating weather clutter. About 30 dB weather clutter rejection is needed of which 15 dB is provided by circular polarization. Filtering of some sort is a viable solution to obtaining the remaining 15 dB. The filtering could be near-optimum as in the case of ground clutter except for the fact that the weather clutter spectrum (see Figure 3) changes with time. This change could be measured and the filter adapted to the spectrum, but this would result in an intolerable amount of hardware.

A good alternative is to use the filter bank produced by the near-optimum ground clutter filter. It is only necessary to set the threshold on each filter adaptively. A so-called "mean level" threshold is employed. Since storms are rarely less than about one mile in extent, the moving clutter is averaged over a half mile on either side of the cell being examined for a target. Each velocity is averaged separately so that filters containing only noise and not weather clutter will not be penalized.

Further, a multiple PRF system, rather than a staggered PRF system[1], is used so that high speed aircraft typically fall in different filters in the filter bank on successive PRF's. There is a very high likelihood that the target return will be competing with noise only and not weather on one of two PRF's. Only for aircraft whose true (not aliased) radial velocity coincides with that of the rain will there be a degradation in detection performance.

In summary, a modern radar for air traffic control use employing a scanning antenna would have a fully coherent transmitter; a linear, large dynamic range receiver; a signal processor containing a near-optimum ground clutter filter bank; a fine grained ground clutter map to set ground clutter thresholds; mean-level thresholding on weather and would employ multiple PRF's for elimination of blind speeds.

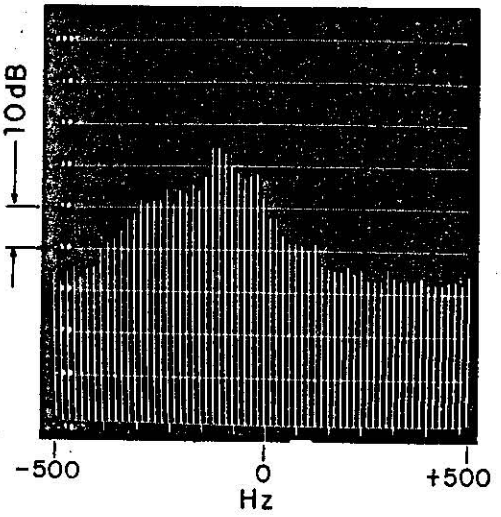


Figure 3

Typical Storm Spectrum Taken Using an S-Band Radar. Receiver Noise Level is -57 dB.

III. SOME EXPERIMENTAL RESULTS

A. Radar Used

A highly modified klystron-type, S-band, FPS-18 SAGE gap filler radar was used to test the signal processing concepts outlined in this paper.

An antenna servo control has been designed, constructed and installed which directs the FPS-18 antenna from digital instructions originating in the radar system timing. In addition to its normal scanning mode, the antenna is also capable of being pointed to a particular azimuth (searchlight mode) by setting the appropriate azimuth coordinate on a set of thumbwheels. Precise speed and position control are desired to allow variation in the speed as a parameter and so that the ground clutter level at each spot can be accurately correlated from scan to scan. Five antenna speeds are available from 5 to 15 rpm.

In the FPS-18 receiver, the original FPS-18 mixer and preamplifier have been replaced by an assembly which includes a microwave sensitivity-time control (STC) attenuator, a balanced hot carrier diode mixer and a semiconductor preamplifier. This change was made to enhance the dynamic range and stability of the system. The original system used an analog STC system in the IF preamplifier. The new STC is controlled by the digital control system through a D/A converter. It generates an R^{-4} curve which will alleviate the angel problem and which incorporates a gain control at the digital control panel.

Instabilities in the transmitter, local oscillators, coherent oscillator and range gate timing give rise to fundamental limitations on the clutter-rejecting capability of MTI radars. Amplitude or angle modulations of the signals in the radar generate sidebands which may fall in the Doppler passband and look to the processor like moving target signals. Similarly, jitter in the timing of the transmitted pulses or the range gates can cause amplitude modulation of the received signals and the consequent sidebands in the Doppler passband.

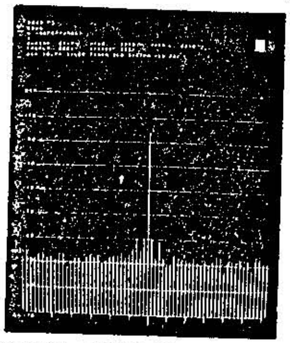
The FPS-18 was originally required to produce a "cancellation ratio" of 40 dB while operating at a fixed pulse repetition rate. This implies that the total spurious sideband power within the Doppler passband of the radar had to be at least 40 dB below the return from a fixed echo at the same range. The radar as designed met this requirement with some margin.

As modified for the FAA, the FPS-18 meets more stringent requirements. The total spurious power in any of the eight Doppler filters is at least 52 dB below the return from fixed clutter at the same range. In other words, the MTI improvement should be 52 dB. This level has been achieved with the FPS-18 operating in a variable PRF mode. Quantitative measurement of these spurious responses is quite difficult. It turns out that the radar receiver and processor make up the best spectrum analyzer available to us. A diagnostic routine known as SGP (Single Gate Processor) is used with the radar antenna stopped in the direction of a known fixed echo (e.g., a large smokestack or radio tower). When the range gate corresponding to the range of the fixed echo is selected, the SGP program performs a Digital Fourier Transform on the received signal and presents the Fourier coefficient (Figure 4). The stability levels shown in Figure 4 were obtained after extensive modification of the original FPS-18 radar.

B. Two Phases of Processor Development

1. General

The signal processing concepts outlined thus far have been tested in a two-phase approach. First, the signal processor was implemented in software on the Lincoln Laboratory Fast Digital Processor (FDP)[10], a very fast, special-purpose computer whose architecture was designed to optimally perform signal processing tasks such as fast Fourier transforms. Second, the signal processing concepts and algorithms tested and proven with the FDP tests were embodied in a hard-wired version, the MTD or Moving Target Detector. The MTD has been designed, built and tested at Lincoln Laboratory and was delivered in June to the FAA at NAFEC where it is undergoing further tests.



KNOWN FIXED ECHO FROM
500-ft STACK AT SALEM MASS.
(range 18 nmi)

VARIABLE PRF	50 dB gain
HORIZONTAL SCALE	± 60 knots
VERTICAL SCALE	10 dB per line

Figure 4

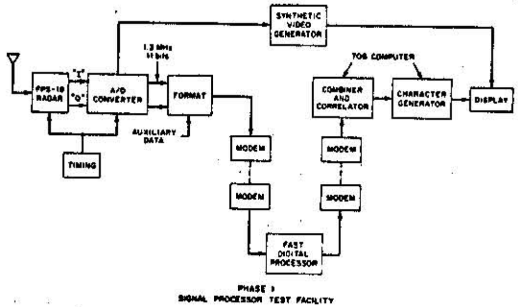


Figure 5

2. Demonstration of Concept Feasibility Using the Fast Digital Processor (FDP)

A block diagram of this phase of the processor development is shown in Figure 5. The FPS-18 receiver output is quadrature-detected and the in-phase and quadrature video signals are digitized. These signals were assembled into a message and sent over coaxial cable from the Lexington Field Station to the main Laboratory where the FDP is located. Since the FDP is a programmable machine, it is easy to adjust processing parameters and alter the processing algorithms. The FDP has the capability of processing an area eight nautical miles in range by 40 degrees in azimuth.

After the radar data was processed by the FDP, the target hit reports were sent over coaxial cable back to the Field Station. A Raytheon 706 minicomputer was used to combine hits from the same target and to interpolate between hits prior to displaying a target character on the ARTS-III display console.

A second signal path shown at the top of the diagram is used to superimpose analog video on the display. The A/D converter outputs are combined to form a synthetic reconstruction of normal video.

Figures 6 and 7 are results obtained from the radar data correlation/interpolation system. This system incorporates software routines to correlate all the reports from a single aircraft and to interpolate between them for increased position accuracy. Figure 6 shows the unprocessed primitive targets. The cluster of threshold crossings at 19 nmi and about 110° is typical of the multiple returns per target. Figure 7 shows 40 scans of radar data that have been correlated and interpolated on a scan-by-scan basis. Only those targets which were derived from more than two contiguous threshold crossings are displayed. The photograph shows the tracks of three moving targets which entered the area of coverage at separate times during the run. Notice that the software routine discriminates against single point returns so that a much higher false alarm rate for primitive returns can be tolerated. Therefore, it is necessary to take into account the correlation/interpolation feature when calculating false alarm rates and detection probability.

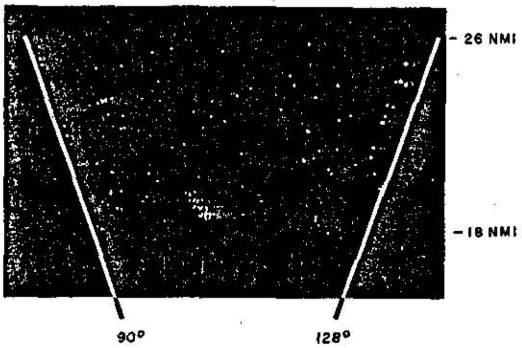


Figure 6

Ten Scans Uncorrelated

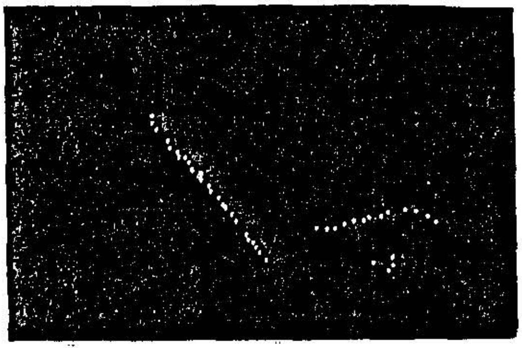


Figure 7

Forty Scans with Correlation and Interpolation

The Phase I tests on the FDP system indicated that the processor concepts performed as theoretical studies has indicated. The processor performed with low false alarm rates and high probability of detection in both heavy ground clutter and rain environments.

3. Moving Target Detection (MTD) - Design, Construction and Testing

a. General

The exact design of the Moving Target Detector (MTD) was proven on a conceptual basis by the tests of the algorithms on the FDP during Phase I. The exact implementation of these algorithms in the MTD was also tested by an extensive computer simulation which uses integer arithmetic and performs truncations and round-offs exactly as they are performed in the hard-wired MTD. The simulation indicated that some of the algorithms used in the thresholding generation were faulty, and that the clutter values stored on disc memory required greater accuracy than was possible with the 10 bits available. As a result, it was necessary to redesign the entire thresholding and disc interface portions of the MTD hardware. Since the new design requires that the clutter values be stored on the disc in floating-point format, floating-to-fixed-point and fixed-to-floating-point converters were included in the disc interface.

b. Moving Target Detection (MTD)

The MTD processor is a special purpose, hard-wired, signal processor which is capable of processing the full 360° coverage of the FPS-18 radar out to a nominal range of 48 nmi. A block diagram of the processor is presented in Figure 8. The I and Q (In-Phase and Quadrature) signals are sampled at a 2.6 MHz rate by a 10-bit A/D converters. The I and Q channels are then added coherently, two at a time, to produce 11-bit I and Q channel words at a 1.3-MHz rate. Ten consecutive samples of both the I and Q channels for each of 760 range gates (47.5 miles of range) are stored in a 8192-word, 36-bit memory. The I and Q channel samples are stored in two 11-bit sections of each 36-bit word; 14 bits are not used. These 7600 words of the 8192-word memory are than processed sequentially (ten time samples for each range cell) by a three-pulse MTI canceller. The I and Q channels are processed by separate hardware in the three-pulse canceller section of the processor. Note that the ten pulses of 11-bit I and Q channel samples exist after the three-pulse canceller as eight pulses of 13-bit words. The output of the three-pulse canceller for both the I and Q channels (real and imaginary parts of the signal) is fed into an 8-point Discrete Fourier Transform (DFT) which produces eight Doppler cells.

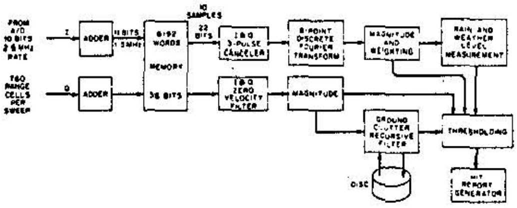


Figure 8

Moving Target Detector (MTD) Processor

Weighting of the I and Q channel signals to reduce the sidelobe level is done after the DFT. Subtracting 1/4 of the signal from the two Doppler cells adjacent to the one of interest is equivalent to a cosine on a pedestal weighting performed in the time-domain.

Since the three-pulse canceller has poor low Doppler velocity response, a zero velocity filter (ZVF) is employed to see low radial velocity targets. This low-pass filter is implemented by coherently adding the first five samples of each of the I and Q channels, respectively, taking their magnitude and adding to this the magnitude of the sum of the last five samples. This gives a somewhat broader frequency response than simply adding coherently all ten samples and then taking the magnitude. The magnitudes of the signals which come out of the three-pulse canceller, DFT and weighting chain are then taken.

After magnitudes are taken, adaptive background levels and thresholds are set and threshold crossings (detections) are noted and output. The adaptive background levels and thresholds are set depending on the clutter phenomenon which is present. The Doppler domain is divided into three domains; Doppler cell 0, Doppler cell 2 through 6, and Doppler cells 1 and 7.

In this Doppler cell 0, the clutter is generally due to ground backscatter. The average ground backscatter cross section varies from range-azimuth cell to range-azimuth cell. The average backscatter signal level for each cell is measured and stored on the disc (see Figure 8). A recursive filter is used to update on a scan-to-scan basis the average signal level stored on the disc. On each scan, 1/nth of the stored clutter level is subtracted from the stored level. One nth of the signal level output from the ZVF is added to the value remaining after subtraction. This new level is then stored on the disc for thresholding in the next scan. The threshold for the 0 Doppler cell is a fixed value between 4 and 8 times the level stored on the disc. This fixed value may be altered by changing a plug in the hardware.

In the Doppler cells 2 through 6, the clutter is due chiefly to rain. For each Doppler and signal cell, the average signal level is measured by averaging the received signal over 16 range cells (one mile) centered on the range cell of interest. The threshold for these cells is a fixed value set at 4 to 8 times the measured average signal level.

Doppler cells 1 and 7 can contain clutter due to rain or spillover from the ground backscatter in cell 0. The threshold set in these cells is the greater of two thresholds: (a) the threshold set as in Doppler cells 2 through 6, or (b) a fixed binary fraction [(1/2 n) n = integer] of the threshold set in cell 0, n is set by use of a wire jumper on the hardware.

Finally, it must be noted that if any I and Q channel sample is noted to have all the bits on (i.e., be in saturation), then any target detections for that range cell are deleted.

c. Moving Target Detector (MTD) Experimental Results

The MTD has been tested at Lincoln Laboratory before its shipment to NAFEC. A block diagram of the experimental set used in these tests is presented in Figure 9. The NOVA 1220 minicomputer is used to format the data from the MTD and to refresh the display. A time exposure photograph of the display for 40 scans of the radar is shown in Figure 10. The STC followed an R^{-4} law and the attenuation dropped to 0 dB at 8 miles. The weather threshold was set to be 6 times the mean signal level, and the ground clutter threshold was set to be 7 1/2 times the level stored on the disc. The range rings appear on the display at 10-mile intervals. There are several small airports in the area as evidenced by the presence of many small aircraft tracks. Logan Airport, Boston, is southeast at 13 nmi.

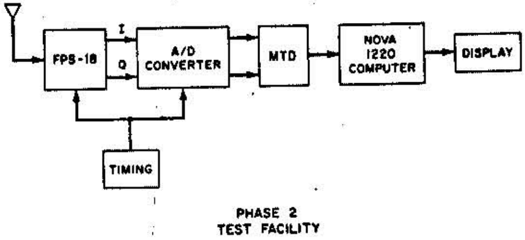


Figure 9

Figure 10

Time Exposure Photograph of PPI Display

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