DIGITAL SIGNAL PROCESSOR FOR AIR TRAFFIC CONTROL RADARS*

C. E. Muehe

M. I. T. Lincoln Laboratory
Lexington, Massachusetts 02173

INTRODUCTION

At a previous NEREM Meeting[1] and in a subsequent paper[2], we described the general philosophy and particular ideas which can be used to overcome the problems associated with achieving good radar detection performance in the presence of various types of clutter; ground clutter (including second-time-around returns), weather clutter and angels (bird flocks).

Recently, a digital signal processor called an MTD (Moving Target Detector) has been designed and built for application to an S-band ASR (Airport Surveillance Radar). This paper describes the MTD and presents some preliminary test results.

The MTD is a special purpose, hard-wired, digital signal processor which is capable of processing a full 360° coverage in 1/16 nmi steps out to a nominal range of 48 nmi. The MTD was designed to provide digital radar output to an automated air traffic control system.

SIGNAL SAMPLING AND STORAGE

A block diagram of the MTD processor is shown in Figure 1. It is preceded by a large-dynamic-range receiver which is linear over nearly the full range of the analog-to-digital converters. This receiver linearity is important to avoid any spectral spreading of the ground clutter returns which would cause them to fall into the Doppler filters and thus reduce the available MTI improvement factor. The hard limiting usually employed reduces the improvement factor by about 20 dB for a 3-pulse canceller.

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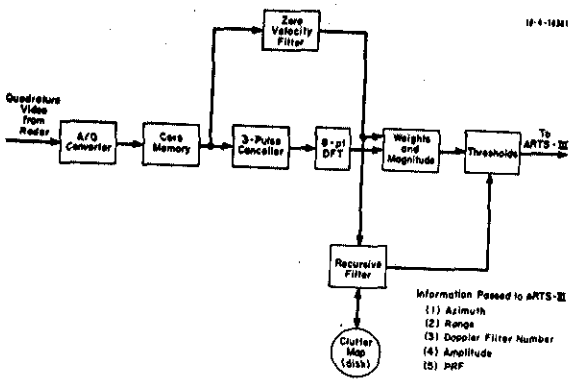


Figure 1

Block Diagram of the MTD (Moving Target Detector) Processor

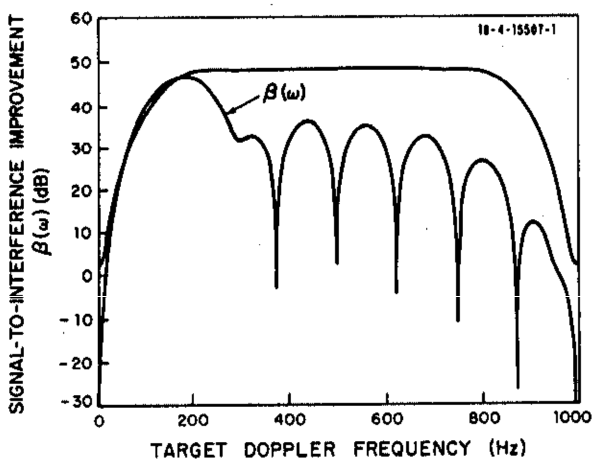
After A/D conversion, the 11-bit words from the two quadrature channels are stored in an 8,000 work core memory. Ten samples from each of 768 range gates are collected at a constant prf. Then the prf is changed about 20% and the data collection process repeated. During collection of 10 samples on the second prf, data collected on the first prf are taken out of the memory. All 10 samples from a particular range gate are taken out in order and fed to the rest of the processor, then 10 samples from another gate, etc.

The 10 samples from one range gate proceed into a 3-pulse canceller followed by an 8-point DFT (Discrete Fourier Transform). These are paralleled by a zero velocity filter. This combination of filters is a good approximation to the so called "optimum processor"[2] for ground clutter.

GROUND CLUTTER FILTER

The responses of the near-optimum filters actually employed are shown in Figure 2. The 3-pulse canceller acts as a clutter filter and the DFT as a set of target filters. To reduce sidelobes, the DFT filters are weighted at their output by subtracting one quarter of the output of each adjacent filter. This is simple to do and provides a cosine on a pedestal type of weighting.

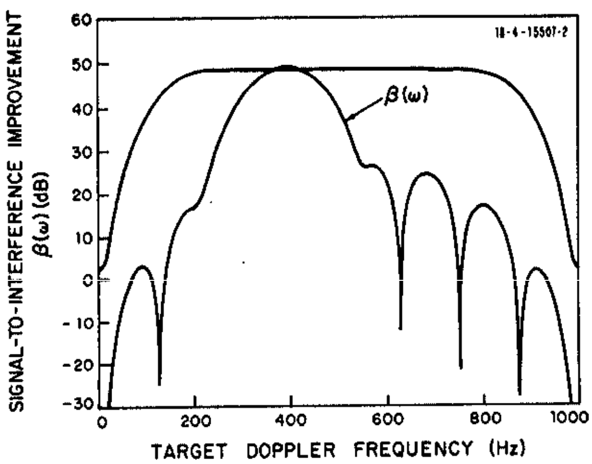
The near-optimum processor is much more easily implemented than the optimum processor. Assuming eight filters, the optimum filters would require 64 complex multiplications per range-azimuth cell. These must be performed in about 8 μsecs giving a rate of 8 million complex multiplications per second or 32 million simple multiplications. The near-optimum processor using a Fast Fourier Transform algorithm requires four simple multiplications by $1/\sqrt{2}$. They are performed in a fixed-wired multiplier which approximates $1/\sqrt{2}$ as $1/2 + 1/8 + 1/16 + 1/64$, $1/256$ and requires only four adders. The remainder of the MTD is also configured so that no multiplications are involved.



(a)

Figure 2

Near-Optimum filter responses. The solid line gives the envelop of responses for optimum filters employing 8 pulses. The near-optimum response utilizing 10 pulses actually exceeds it in places. (a) Filter tuned to 125 Hz, (b) Filter tuned to 375 Hz



(b)

GROUND CLUTTER MAP

Study of ground clutter shows that it varies appreciably from one resolution cell to the next. There exist many shadow area within the clutter where aircraft compete only with noise for detection. For thresholding purposes, so as to get the best ground clutter estimate and the best possibility of aircraft detection, a fine-grain ground clutter map is incorporated in the MTD (see Figure 1).

The azimuth coverage of the radar is broken into 480 Coherent Processing Intervals (CPI's) each about one-half antenna beamwidth in extent. During one CPI, ten pulses are transmitted at a constant prf. The prf is changed for the next CPI. The clutter map is a disc memory holding 480 x 768 = 368,640 clutter words, one for each range resolution cell in each CPI. The clutter words are stored in 10-bit floating point format to preserve the large dynamic range of the clutter signals.

The ground clutter map levels are built up using a recursive filter which adds on each scan 1/8 of the magnitude of the zero velocity filter output to 7/8 of the value stored in the clutter map. The map requires about 10 to 20 scans to establish steady clutter values. To build up an accurate clutter map, careful registration of the clutter map with the true pointing direction of the antenna is essential. This is achieved by breaking up each revolution of the antenna, marked by 4096 Azimuth Change Pulses (ACP's) into 240 units containing 17 or 18 ACP's each. Each unit contains 2 CPI's. The disc is accessed every two units (34 to 36 ACP's, approximately 44 msec), during which time 4 CPI's worth of ground clutter data is read onto and off of the disc. The disc has a maximum access time of 18 msec. Two, 3000-word MOS buffers are used to store the data for use in the processor.

The ground clutter map values multiplied by a constant are used to establish thresholds in the zero velocity filter (number 0). A multiplier of 4 to 8 is used. In the two filters immediately adjacent (numbers 1 and 7), wherein theory says a ground clutter residue of about -40 dB exists, another appropriate multiplier is used. These multipliers are powers of two or the sum of two powers of two, so they are implemented with shifts and adds.

SECOND-TIME-AROUND CLUTTER

When the MTD is used with a klystron-type transmitter the so called second-time-around clutter returns are filtered out as well as normal clutter returns. These returns are due to illumination of the ground by the next to last pulse transmitted and are prominent in mountainous regions or when weather conditions cause long-range anamolous propagation. The constant prf (during a group of 10 pulses) unlike staggered prf, assures that the same clutter will be illuminated by the second to last pulse on each transmission. The klystron, unlike the magnetron, assures a fixed phase relation between the last and next-to-last-pulse clutter returns so that both will be filtered out simultaneously.

WEATHER FILTERING - Coherent vs. Non-Coherent Integration

Precipitation returns typically have a spectral width of about 25 knots with a center velocity that may be anywhere from -60 to +60 knots depending on wind conditions relative to the pointing direction of the antenna. For moderately heavy rain at 30 nmi range, rain return in an ASR is about 13 dB above one-square-meter.

Approximately, a +15 dB signal-to-interference ratio is required for automatic detection so we could use a total improvement in signal-to-clutter ratio of about 30 dB. Circular polarization provides about 15 dB so that some form of filtering or integration is required.

Attempts to build a digitizer which works well in rain have failed in the past due to a lack of recognition of the correlation properties of the clutter. Rain clutter signals are partially correlated from pulse to pulse so that non-coherent integration in the azimuth direction produces random signals whose variance is much greater than if the rain signals were noiselike[3] (uncorrelated). This greater variance requires a large increase in detection threshold value over that set for noise and a consequent loss in detectability of aircraft targets. If the threshold is not reset, a high false alarm rate in rain results.

The MTD uses coherent integration of pulses instead of non-coherent. Coherent integration or filtering takes advantage of the correlation properties of the rain clutter. A DFT filter bank of eight filters is implemented in each range-azimuth cell. The rain return occurs in not more than three adjacent filters (see Figure 3). A target in any of the other filters competes with noise only for detection.

Further, the prf is changed by about 20% from group to group of 10 pulses so that a higher velocity target will be aliased into a different filter on each prf (see Figure 3). Thus, all targets will be free of weather clutter on one of the two prf's, except for those whose radial velocity is equal within about 25 knots to that of the rain.

A weather or noise threshold is established for any one filter, say filter number 3, by summing the detected outputs of filter 3 in eight range cells on one side and seven on the other side of the cell of interest, dividing by 15 to find the mean and multiplying by a constant "a" to establish the threshold. Since only coherent integration has been performed, the 15 outputs are statistically independent Rayleigh distributed numbers regardless of whether from noise or rain clutter so that the multiplying constant "a" to give a certain false alarm rate doesn't change as weather comes into the area. Figure 4 shows the false alarm rate as a function of threshold setting when averaging over various numbers of statistically independent samples. Note that for 15 and a probability of false alarm of 10^{-6}, the threshold is only 2 dB above that derived assuming perfect knowledge ($N = \infty$) of the rain or noise conditions. The use of this type of mean-level threshold assumes that the rain level is constant over 15 cells (~1 nmi) of interest. The experience with rain to date indicates that an increase in the threshold of, at most, 1 or 2 dB will account for the variability of rain level over the region of interest.

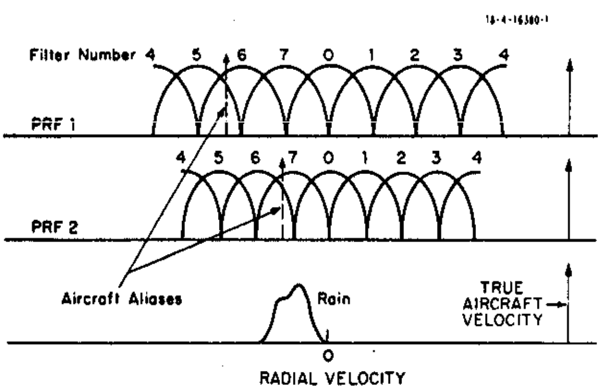


Figure 3

Schematic diagram of Multiple prf response to rain and aircraft illustrating the Doppler foldover effect. Foldover occurs whenever the sampling rate is too low.

To summarize the thresholding: (a) the zero velocity filter is thresholded using the ground clutter map output, (b) filters 2 through 6 are thresholded using the mean-level threshold described above and (c) for filters 1 and 7 both a ground clutter threshold and a mean-level threshold are calculated and the larger of the two is used to threshold the signal.

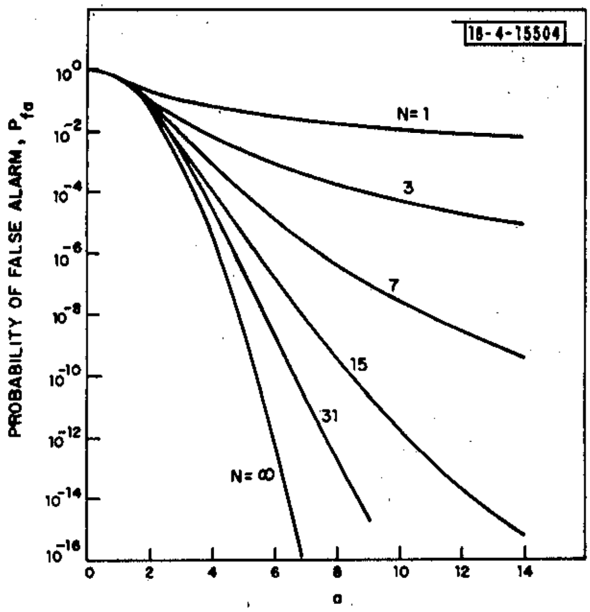


Figure 4

False alarm rate as a function of threshold setting "a". The parameter N is the number of uncorrelated samples averaged to determine the threshold.

PHYSICAL DESCRIPTION OF MTD

Figure 5 is a picture of the MTD. Standard TTL circuits are used except for the MOS buffer to the disc memory. The construction utilizes wire-wrap boards to hold the integrated circuits. Besides the input core memory and the clutter map disc memory, the MTD consists of approximately 900 integrated circuits. The MTD includes all of the digital timing for the radar and generates the 31-MHz, 0.8 μsec pulse which is upconverted in the transmitter to S-band to become the transmitted pulse

PRELIMINARY TEST RESULTS

The MTD was tested with a highly modified FPS-18, klystron-type radar with characteristics similar to the ASR-8. The radar was modifie to improve its stability by the addition of a shunt regulator on the klystro high voltage power supply and replacement of the entire vacuum tube exciter and stalo with functionally equivalent solid-state equipment. The stability is such that when looking at a fixed reflector (large water tower) in the field, with the antenna stationary, the instability sidebands are below the system noise. The total instability sidelobe power is thus more than 45 dB below the carrier allowing improvement factors at least as good as those shown in Figure 2.

The MTD radar has been operated for about a month at this writing. Figure 6 shows a multiple scan picture of the PPI. The raw output of the radar in digital form was displayed in synthetic form as a dot for each detection in a given range gate for one CPI. Typically, a medium-sized target would be detected and displayed as several dots. The antenna beam was tilted to zero degrees elevation angle instead of the usual few degrees upward to provide good detection of low flying, small aircraft (~1000 ft altitude) out to beyond 20 nmi. The excellent filtering in the MTD removed virtually all the fixed ground clutter. Automobile and truck traffic is visible on certain roads generally within 5 miles of the radar. These are very repeatable returns that can easily be removed in a tracking computer.

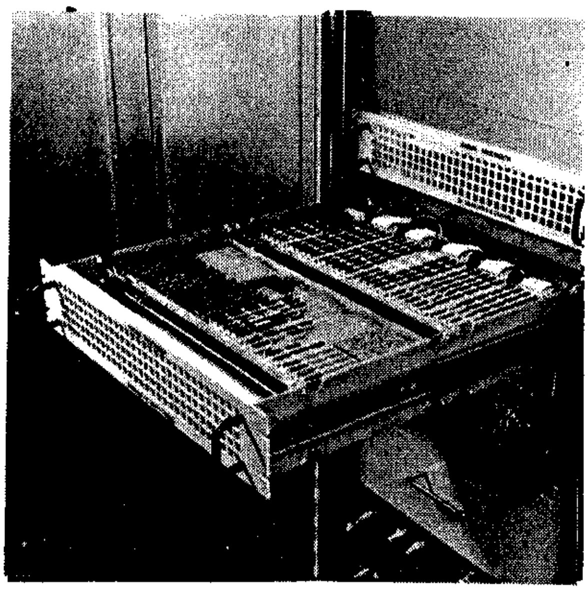


Figure 5

Photograph of the MTD processor with one drawer opened. The MTD less power supplies occupies 23" of 19" rack space.

Future plans call for the MTD radar to be moved to NAFEC, the FAA's national testing facility in Atlantic City, where it will be connected to an ARTS-III (Automated Radar Terminal System) and used in extensive operational flight testing.

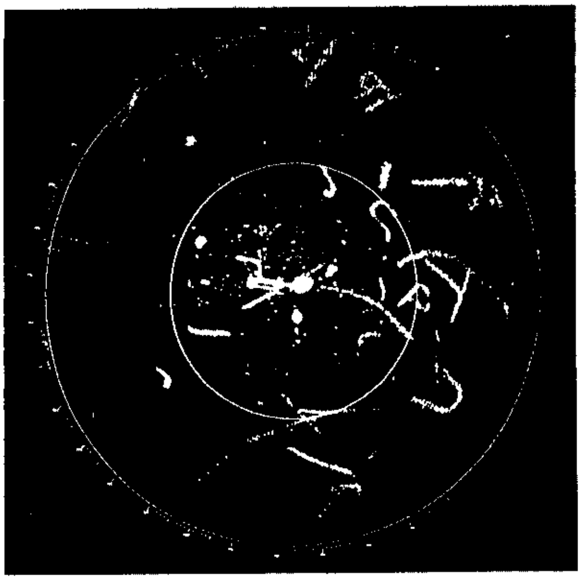


Figure 6

Scan exposure of PPI. Maximum range is 20 nmi The camera lens was left open for 40 scans; about 3 1/2 minutes

In conclusion, we believe the MTD to be a practical processor with greatly improved performance in detecting aircraft against weather and ground clutter, including second-time-around effects. The MTD will allow radars to be sited at higher elevations with antenna patterns tilted down to detect longer range, low flying aircraft. The probability of false alarm is low enough and the probability of detection on practically all aircraft within its coverage is good enough for automatic tracking.

ACKNOWLEDGEMENT

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