ADVANCES IN RADAR SIGNAL PROCESSING*

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SUMMARY

The recent availability of new solid-state digital components has made possible the development of radar signal processing techniques only dreamed of in the past. The philosophy and design of these techniques is described in terms of a new signal processor for Airport Surveillance Radars called the Moving Target Detector (MTD). Test results showing greatly improved automatic aircraft acquisition and tracking are discussed.

Gradually over the past few years, inexpensive new solid-state components have been introduced which make possible the design and construction of digital signal processors only dreamed of in the past. This is especially true in the radar area where doppler filtering had usually been limited to analog or digital delay line cancellers. Inexpensive components now allow the construction of digital filters in each range-azimuth resolution cell so as to optimize the improvement to the signal-to-ground clutter ratio for each target velocity. Cost of components generally doesn't limit available performance.

Digital processing has many advantages over analog. Digital filters are perfectly repeatable eliminating drifts due to component changes with time. Digital filter responses are exactly predictable and do not depend on component tolerances as do analog. Digital filters have no tuning to get out of adjustment. Finally, digital filters are typically implemented in a sequential manner using the same computing hardware over and over again. As a result, the cost of increasing the number of digital filters, does not increase as fast as the number of equivalent analog filters. In numbers of a few hundred or more, digital filters are generally cheaper than analog.

As an example of the use of these new design techniques, I would like to describe a digital signal processor which has been under development over the past few years. The new processor called the Moving Target Detector (MTD) is designed to optimize the performance of the FAA's Airport Surveillance Radars (ASR) when used in an automated environment. For several years the ATCRBS beacon replies have been digitized and introduced into a computer system (part of the Automatic Radar Terminal System, ARTS-III) so that automatic tracking of all beacon-equipped aircraft became routine. Unfortunately the same success was not achieved with returns from primary radar.

Initial studies showed that this lack of success with radar tracking was due to either an excess of false alarms from various forms of clutter (ground, rain, bird returns) or due to a lack of detectability of aircraft flying in clutter areas. Analysis shows that, in a noise environment, a probability of detection of 0.8 or higher per scan and a false alarm rate less than 10^{-5} will produce good tracking of aircraft. However, due to the requirement to follow manuevering aircraft, the tracker must have a fast transient response so that aircraft are typically dropped from track when not detected on three successive scans. Thus the detection and false alarm requirements quoted above assume that detection dropouts are uncorrelated from scan-to-scan. When an aircraft enters a clutter region, this requirement is not met. Detection is missed on a few scans, and the aircraft track is dropped.

For this reason, detectability in clutter of all kinds is critically important to the success of an automated radar system. Studies showed that the MTI improvement factor in ground clutter should be about 50 dB instead of the 20 to 30 dB experienced in most ground-based surveillance radars. At the 50-dB level, reduced detection will occur only in very small isolated ground-clutter regions. In addition, blind speeds must be eliminated especially those at zero radial velocity. A small aircraft flying by at longer ranges will typically go undetected on five to ten scans as it passes through the tangential point. It is regularly dropped from track when conventional MTI circuits are employed. When flying in the rain, aircraft often go undetected due to the radar's lack of any subweather visibility. Studies show that approximately 15 dB of subweather visibility is required to see small aircraft in heavy rain.

In many areas, the so-called second-time-around effect occurs wherein ground reflections occur due to illumination of the ground by the second-to-last pulse transmitted. It is easy to see that circuits designed to eliminate close-in clutter will not also eliminate second-time-around clutter unless a constant PRF is employed and unless the transmitter is coherent from pulse-to-pulse so that a fixed phase relation exists between the returns from the last pulse and the second-to-last pulse.

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Radar returns from bird flocks (angels) are also a problem. Fortunately, angels can be discriminated against by the size of their radar returns.

Not only must solutions be found to solve the detection and false alarm problems associated with each of the phenomena discussed above, but the solutions chosen must be compatible with each other. For instance, the constant PRF requirement to eliminate second-time-around clutter is not compatible with the usual staggered PRF used to eliminate blind speeds when conventional MTI cancellers are employed.

Description of the MTD

The solution to the problems involved in automating the ASR have been solved by the application of modern digital processing techniques. Figure 1 is a photograph of the resulting processor, called the Moving Target Detector (MTD). The signal to be processed is taken at IF from the output of the IF preamplifier and fed through a special linear, wide-dynamic-range amplifier to the quadrature video detectors. These are mounted in a chassis near the bottom of the rack (Figure 1). The two quadrature video detector outputs are converted to 10-bit digital numbers by the analog-to-digital converters shown and hence into the digital processor which occupies the two feet of rack space just below the converters. The MTD contains an 8000-word input memory and about 900 integrated circuits. A disc memory is used as a fine-grained ground clutter map. All the parts in the entire rack cost approximately $25,000.

The MTD achieves its superior performance principally through fine resolution linear filtering and adaptive thresholding techniques. As Figure 2 depicts, on each scan of the antenna, the entire coverage area is broken into 1/16 nm by 3/4 degree range-azimuth cells, approximately 370,000 in all. In each 3/4 degree azimuth interval, called a Coherent Processing Interval (CPI), ten pulses are transmitted at a constant PRF. The ten complex digital samples collected in each range-azimuth cell are processed to form eight Doppler filters which span the PRF interval. The radar output is thus divided into 2,900,000 range-azimuth-doppler cells. Each is adaptively thresholded as explained below.

Ground-Clutter Filters and Thresholding

The filters depicted in Figure 2 are not simple filters, but rather they have been tailored for best rejection of ground clutter using linear wide dynamic range processing. It is possible to achieve MTI improvement factors well in excess of those achieved in present-day ASR's. The comparison is depicted in Figure 3. Here the upper curve is the envelope of the MTI improvement factor when using the optimum filters employed in the MTD, and the lower curve is the corresponding curve for the usual three-pulse canceller employed in an ASR following a limiting IF amplifier. Notice that approximately 25 dB greater improvement factor is achieved and a much narrower notch is experienced at zero velocity and the blind speeds.

Virtually all of the ground-clutter returns appear in filter zero (see Figure 2) with a little bit spilling over into filters 1 and 7. Because ground clutter is so spotty in nature, i. e. varys widely in value from spot-to-spot on the ground, great difficulty is experienced in calculating appropriate threshold values for detection. To solve this problem a digital ground clutter map is implemented with one word for each range-azimuth cell, 370,000 words in all. These are stored on the magnetic disc memory.

The map value is built up in a recursive manner by adding 1/8 of the output of the zero velocity filter on each scan to 7/8 of the value stored in the map. Thus, as rain moves into the area or as propagation conditions change, the clutter map value changes accordingly. The value stored in the map is multiplied by an appropriate constant to set the threshold for the zero velocity filter. Since the clutter signals appear at the output of the 1 and 7 filters, much attenuated, the clutter map value is also used to set one of two thresholds in these filters. The other is a mean-level threshold as described below.

Weather Clutter and Mean-Level Thresholding

Unlike ground clutter which has a constant spectral width centered at zero velocity, precipitation returns have a spectral shape which varies in width as well as average velocity[1]. Its shape is set by the wind field occupied by the rain. Wind velocity variations with altitude set its spectral width and the average wind velocity with respect to the radar sets the mean doppler.

If the set of eight doppler filters which were optimized to reject ground clutter are weighted properly, they will have moderately low sidelobes (15 to 25 dB) and thus produce good discrimination between aircraft and rain at different velocities.

This is depicted in Figure 4. A typical rain spectrum is shown on the bottom line and the very narrow spectrum of an aircraft to the right. The PRF of the radar is changed about 20% on successive CPI's (groups of ten pulses). The aircraft's spectrum folds over (aliases) differently on each PRF so that it appears in filters 5 and 6 on PRF-1, but in filters 6 and 7 on PRF-2. In the example depicted in Figure 4, the aircraft will compete with the rain for detection on PRF-2, but it appears in one filter without any rain return (filter 5) in PRF-1. Thus using two PRF's, the target appears in at least one filter free of rain over the whole velocity region from -600 to +600 knots except for the small region (approximately 30 knots wide) when the targets radial velocity is exactly that of the rain.

The MTD is thus said to have subweather visibility. It can see aircraft whose cross-section is many dB below the radar cross-section of the weather return. This feature was not previously available in ASR's and accounts for the MTD's excellent tracking ability of aircraft in rain.

The other nice feature of the filter bank approach is the facility with which proper thresholds can be established taking into consideration the presence of the rain. Again, referring to Figure 2 for each filter number, the detection threshold is established by summing the detected output in 16 range cells - eight on either side of the cell of interest. Thus each filter output (except filter zero) is averaged over one mile in range to establish the statistical mean level of the rain clutter or noise in each velocity increment. The mean levels are then multiplied by an appropriate constant to establish the desired false alarm level. If the signal in a particular filter exceeds this threshold, a target declaration is made and a digital hit report is generated.

The hit report contains the azimuth, range and amplitude of the target return as well as the filter number and PRF employed. As the antenna scans by a typical large aircraft as many as 20 hit reports may be generated in different filters, on several CPI's and in two range gates. These digital hit reports are passed on to a post processor where all the reports which appear to come from a single aircraft are grouped together (correlated). An interpolation process is then used to find the best azimuth, range, amplitude and radial velocity to the aircraft after the correlation-interpolation process and further sector thresholding based on target amplitude and doppler to reduce the angel count, the target reports are delivered to the tracker. The tracker further eliminates false hit reports which do not form tracks. Finally, the tracker output is displayed on the scope for use by the air traffic controller.

Flight Evaluation Results

The MTD was connected to an ASR radar at the FAA's experimental facility (NAFEC) at Atlantic City, New Jersey, and extensive flight testing was used to evaluate its operational performance. It was compared to a conventional ASR-7 and to an ASR-7 equipped with a digital MTI and a modern sliding-window digitizer. The two radars to be compared were diplexed onto a common antenna so that they were looking at the same aircraft and clutter environment at exactly the same time. The transmitter powers and receiver sensitivity were adjusted so that the round trip sensitivity of the two against noise were identical to within 1 dB. What follows represents a small sampling of the rather extensive test results.

Detection in Ground Clutter

Ground clutter is not very extensive at NAFEC. The largest clutter returns are from large buildings in Atlantic City about eight miles SE of the radar site. The clutter level varies up to about 45 dB above noise.

The controlled aircraft was a small Piper Cherokee flying about 1000 feet above ground level. Figure 5 is a 56-scan display of the tracker output. Note the meaning of the symbols employed. It was typical that the MTD produces almost 100% probability of detection over ground clutter, whereas the sliding-window detector had many radar misses in a row. If it were not for the beacon replies, the track would have been dropped several times in the sliding-window detector case.

Also in Figure 5, we see the track of a non-beacon-equipped aircraft (radar only). Notice how this track is dropped in the sliding-window case when the aircraft flies tangential to the radar. This illustrates the value of the ground clutter map in seeing zero-radial-velocity targets. Even over clutter there is a high probability of seeing zero-radial-velocity aircraft with the MTD because of the very large (100 to 1000 m^2) cross-section presented by the side of an aircraft. Conventional MTI, however, puts an absolute null at zero velocity giving no hope for detection of tangential aircraft.

Detection in Rain

Figure 6 depicts what happens in a rain storm. With its subweather visibility, the MTD experiences no difficulty detecting aircraft in rain. It tracks non-beacon-equipped aircraft in rain as well as if they were in the clear. As seen in Figure 6, rain causes loss of radar detection (B is for beacon detection only) for the sliding-window detector. The false alarms were controlled quite well by the sliding-window detector because it measured the intensity and correlation properties of the rain clutter and raised its threshold accordingly(2). Unfortunately with this raised threshold, it could not detect the aircraft. Again, if the aircraft were not beacon equipped, it would not have been tracked in the region where extensive B's occurred.

Crossing Tracks

A special test was performed using two aircraft flying in the clear. A small aircraft (Piper Cherokee) flew a nearly straight path and a somewhat larger aircraft (Aero Commander) flew slightly higher in altitude in an S-shaped path so as to cross the path of the smaller aircraft at exactly the same time. The result is depicted in Figure 7. Notice that there was even a third aircraft flying in the vacinity of the first two. All were perfectly tracked using the MTD.

Position Accuracy

Approximately 100 tracks were analyzed to establish and compare range and azimuth accuracies. Only long tracks with over 90% blip-scan ratio were employed. A high-order polynomial curve (typically fifth order) was fitted separately to the azimuth versus scan number curve, and the range versus scan number curve of each track. The standard deviation of the departure of the measured quantity (range or azimuth) from the fitted curve was determined. The resulting histograms of the standard deviations are shown in Figures 8 and 9. The MTD results were close to the beacon results. The azimuth accuracy for the MTD is typically substantially better than that for the sliding-window detector.

Conclusions

The MTD offers a new class of capability for ground-based air surveillance radars. Tests show that a radar equipped with MTD can track aircraft everywhere within the surveillance column of the antenna. The tracking is automatically initiated and the tracks are continuous despite ground and weather clutter and birds (angels). The radar now can be sited freely without consideration of ground clutter limitations.

Further, the false alarm rate is so low that after a small amount of processing, the entire radar's output can be reliably transmitted over a narrow bandwidth telephone line. The MTD has no tuners or adjustments of any kind. It is an economical solution to the radar automation problem. These advances in the state-of-the-art have been made possible by the great advances in digital technology over the past few years.

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REFERENCES

(1) C. E. Muehe, et. al, "New Techniques Applied to Air-Traffic-Control Radars", Proc. IEEE, Volume 62, Number 6, pages 716-723 (June 1974)

(2) W. S. Reid, M. R. Saltsman, L. E. Vogel, "Technique for Clutter False Alarm Control in Automated Radar Detection Systems", IEEE 1975 International Radar Conference Record, pages 294-299.