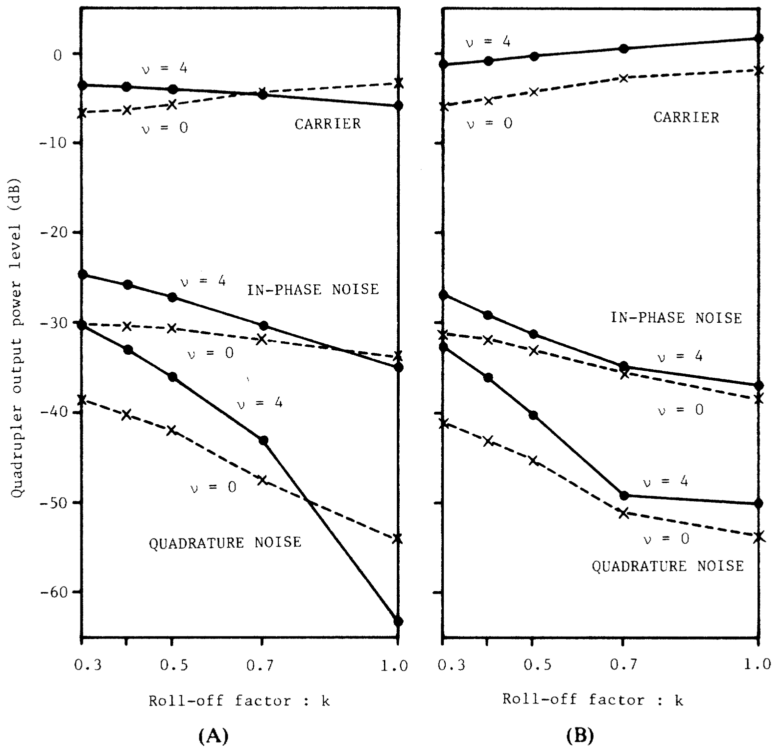

Fig. 3. (A) Full cosine roll-off. (B) Half cosine roll-off. Quadrupler output carrier and noise power; noise power is evaluated in the vicinity of the center frequency with frequency slot of 1/256 T Hz, where T = symbol length.

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CTD MTI RADAR FILTER WITH CHARGE-TRANSFER INEFFICIENCY COMPENSATION

The design and implementation of a second-order nonrecursive moving target indication (MTI) radar filter using commercially available charge-transfer devices as delay lines are described. A simple technique is included to compensate for the device charge-transfer inefficiency and its sensitivity is analyzed.

Experimental laboratory tests and results in an operating radar system are reported showing the good performance of the realized MTI radar filter.

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I. INTRODUCTION

The operation of present-day tactical and surveillance radars in heavy clutter environments requires efficient means to extract moving targets from the clutter background. The criterion of discrimination between the two types of radar return signals uses their associate Doppler frequency shifts. A moving target indication (MTI) filter is employed to suppress the low frequencies of the clutter echoes. The MTI filter operates on a pulse train modulated by the received Doppler frequencies obtained after demodulation of the echo signals to the video range and is able to discern moving targets even in the presence of clutter echo signals many orders of magnitude greater.

In particular, digital recursive and nonrecursive MTI filters have been proposed for clutter suppression in operating radar systems [1-3] for their inherent stability and flexibility. The performance of digital MTI filters can be very satisfactory if digital words of sufficient length are employed, especially when a large dynamic range is required. However, the presence of analog-to-digital conversion and the necessary digital circuitry give rise to a solution for the MTI problem that in some applications may have an excessive cost or whose technical realization may be precluded because of physical dimensions, weight, power consumption, or pulse-repetition frequency (PRF) value.

More recently the advances in charge-transfer device (CTD) technology have shown the technical feasibility of an analog discrete-time solution to the MTI problem [4, 5], which may provide satisfactory performance while maintaining the characteristics of flexibility and good performance at a low cost. CTDs can be used as the delay lines required in first- and higher order MTI filters. However, they are not ideal delay lines and one of the major contributions to their nonideal behavior comes from the charge-transfer inefficiency (CTI), i.e., from the fraction ϵ of the stored signal sample that remains behind at any transfer step [6].

The design and realization of a second-order MTI filter implemented by commercially available CTD delay lines is described here. In Section II the problem of the CTI is considered in particular. A simple and efficient technique for compensating the CTI effects is illustrated and its sensitivity is analyzed. Section III shows the performance of the CTI-compensated second-order MTI filter obtained in laboratory tests and in connection with an operating radar system.

II. CTD MTI FILTER

A. CTI Compensation Technique

In a radar system at the input of the digital or discrete MTI filter the whole-range echo signal is sampled at an appropriate rate $1/T$, in order to prevent unacceptable loss in detectability [1]. Hence the MTI filter must delay the echo signal samples by multiples of NT, where $N = T_r/T$ is the total number of echo signal samples contained in one radar interpulse period T_r = /PRF. In particular it is known [1] that the operation of a nonrecursive second-order (three-pulse) MTI filter is characterized by a z-transfer function

$$G(z) = 1 - 2z^{-N} + z^{-2N} \tag{1}$$

where z^{-1} is the delay operator associated with the sampling frequency $1/T$.

The filter (1) can be implemented by using two N-stage CTD delay lines as shown in Fig. 1. However their CTI ε causes the actual transfer function to deviate from its ideal value z^{-N}. Assuming the product $N\varepsilon \ll 1$ (a condition almost always satisfied in practical applications), it was shown in [7] that an N-length transversal filter, designed to have a desired transfer function $H(z)$, when realized using CTD devices having a CTI value ε, gives rise to an actual transfer function $H'(z)$ expressed by

$$H'(z) = H(z) + \varepsilon(z - 1)[dH(z)/dz]. \tag{2}$$

Hence for an ideal delay line $D(z) = z^{-N}$, the actual transfer function $D'(z)$ becomes

$$D'(z) = (1 - N\varepsilon)\, z^{-N} + N\varepsilon\, z^{-(N+1)} \tag{3}$$

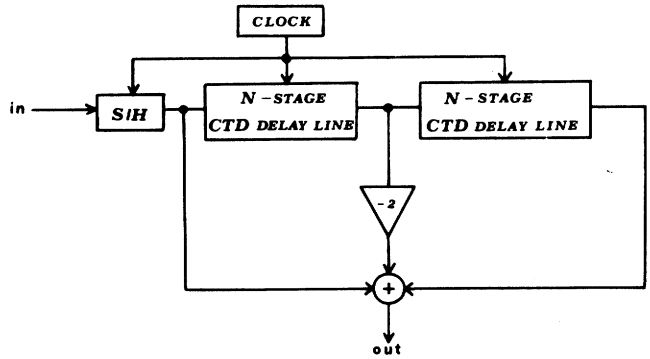

Fig. 1. Structure of second-order nonrecursive MTI filter using CTDs.

which corresponds to an actual impulse response

$$d'(t) = (1 - N\varepsilon)\, \delta(t - NT) + N\varepsilon\, \delta(t - NT - T) \tag{4}$$

instead of the desired one

$$d(t) = \delta(t - NT) \tag{5}$$

where $\delta(t)$ is the Dirac delta function.

As a consequence of the attenuation $1 - N\varepsilon$ of the first pulse and the presence of the second pulse in the actual response (4), clutter residues will remain at the MTI filter output of Fig. 1.

The CTI effects on the CTD delay line can be eliminated by cascading a suitable equalizer filter $E(z)$ to the transfer function $D'(z)$. The equalizer $E(z)$ has to satisfy the relation

$$D'(z)\, E(z) = z^{-N}. \tag{6}$$

From (3) it follows for $E(z)$

$$E(z) = 1/[(1 - N\varepsilon) + N\varepsilon\, z^{-1}] \tag{7}$$

which can be easily realized as a first-order recursive discrete filter. The resulting structure of the equalized CTD delay line is shown in Fig. 2. The input and output waveforms of a CDT delay line with and without the CTI compensation accomplished by the equalizer (7) are shown in Fig. 3. In Fig. 3(A) the output signal distortion due to the device CTI is very clear, while in Fig. 3(B) the output signal appears to have been well equalized. In this test T was equal to 2 μs and the measured product $N\epsilon$ was 1/12, with N equal to 256.

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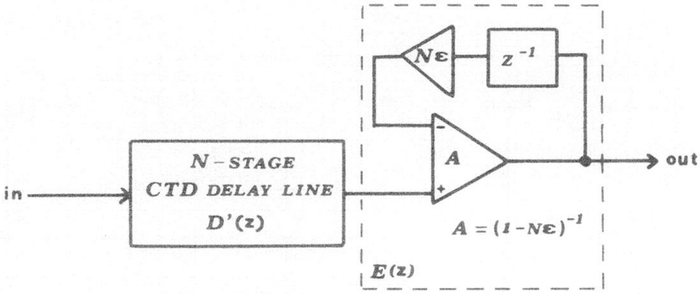

Fig. 2. Structure of CTI-compensated CTD delay line.

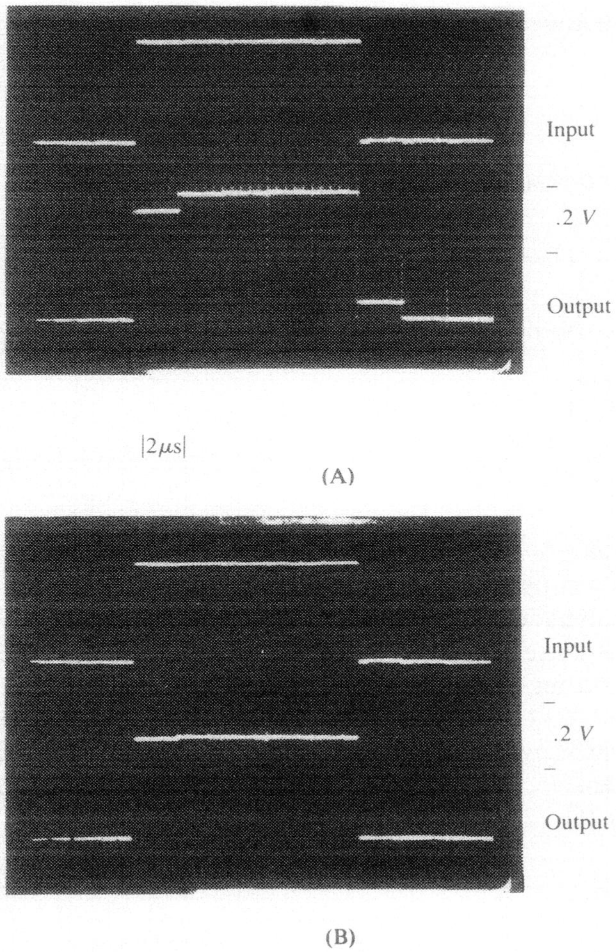

Fig. 3. Delay line input and output waveforms. (A) without CTI compensation. (B) with CTI compensation.

B. Sensitivity Analysis

The equalizer of Fig. 2 compensates for a fixed value of the product $N\varepsilon$. However, changes in ε (e.g., owing to temperature or clock rate variations) can be appropriately accommodated by measuring at intervals the product $N\varepsilon$ and changing the feedback loop weight and the amplifier gain accordingly in an automatic or externally controlled way.

In the following, a sensitivity analysis of the compensation technique due to variations of the CTI from its nominal (or measured) value is given.

Let us suppose that in the CTD delay line of Fig. 2, equalized for a specific CTI value ε, the charge transfer loss changes to a new value $\varepsilon' = \varepsilon + \Delta\varepsilon$. The overall transfer function $M(z)$ of the system of Fig. 2 is the cascade of (3), evaluated for the new value ε', and of (7)

$$M(z) = \{[(1 - N\varepsilon') + N\varepsilon' z^{-1}]/[(1 - N\varepsilon) + N\varepsilon z^{-1}]\}z^{-N} \tag{8}$$

whose inverse z transform is [8]

$$m(t) = [(1 - N\varepsilon')/(1 - N\varepsilon)]\ \delta(t - NT) + [(1 - N\varepsilon')/(1 - N\varepsilon) - \varepsilon'/\varepsilon] \sum_{k=1}^{\infty} [-N\epsilon/(1 - N\epsilon)]^k\ \delta(t - NT - kT). \tag{9}$$

The assumption $N\varepsilon \ll 1$, and of course also $N\varepsilon' \ll 1$, implies that only the first two terms are of practical interest. Hence (9) can be approximated as

$$m(t) \cong (1 - N\,\Delta\varepsilon)\ \delta(t - NT) + N\,\Delta\varepsilon\ \delta(t - NT - T) \tag{10}$$

which is of the same form of the nonequalized CTD delay line impulse response (4), with ε replaced by $\Delta\varepsilon$.

The result shown in (10) may be exploited to find a bound for the deviation $\Delta\varepsilon$ of the device CTI from its nominal value ε used in the equalizer, according to the acceptable level of clutter residues at the MTI filter output.

III. IMPLEMENTATION AND PERFORMANCE OF THE CTD MTI FILTER

The complete structure of the second-order CTD MTI filter including the CTI compensation is illustrated in Fig. 4 and its performance was verified by laboratory tests and in an operating radar environment. It can be observed that the final adder of the filter of Fig. 4 works on sampled signals, differently from other reported approaches [4, 5] that add signals after their reconstruction in continuous form. The solution of Fig. 4 was preferred because it leads to an accurate time quantization and alignment of the signals at the three adder inputs without requiring the presence of equal transmission networks for the reconstruction of the continuous signals along the three different paths.

The actual implementation of the equalizer $E(z)$ as the first-order recursive filter of Fig. 2 is straightforward. The operation z^{-1} does not require any additional delay element like a CTD cell, but is appropriately realized by means of a sample-and-hold circuit at the differential amplifier output.

One also observes that in response to asynchronous interference pulses the only effect of the recursive struc-

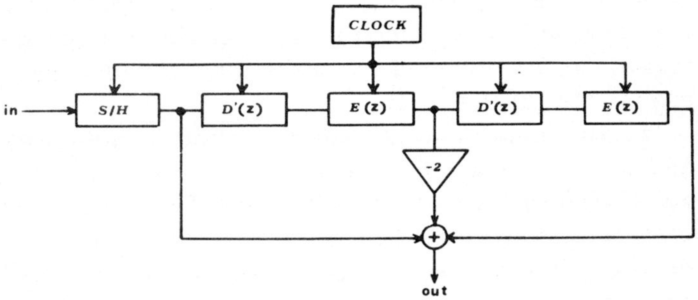

Fig. 4. Structure of CTI-compensated second-order nonrecursive MTI filter.

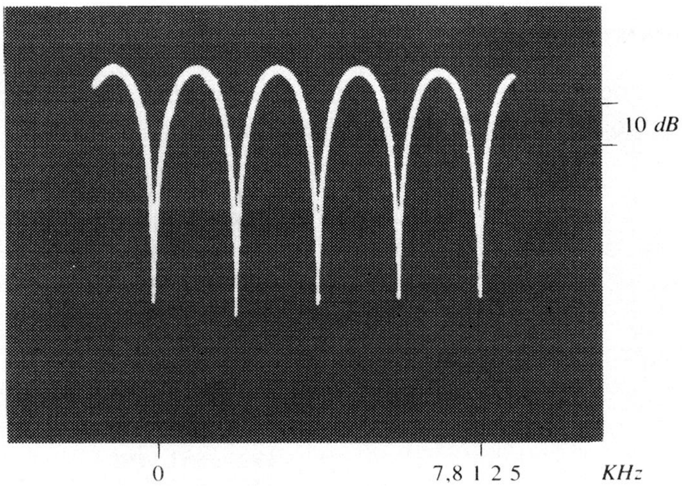

Fig. 5. Frequency response of MTI filter with 1/PRF = 0.512 ms.

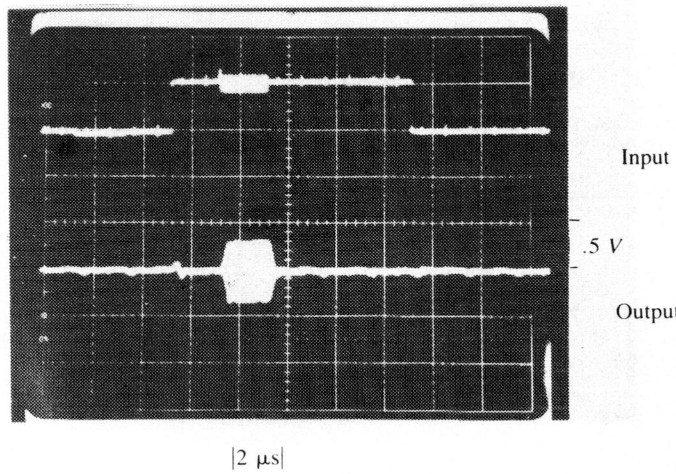

Fig. 6. MTI filter input and output signals, simulating simultaneous presence of target and clutter echoes.

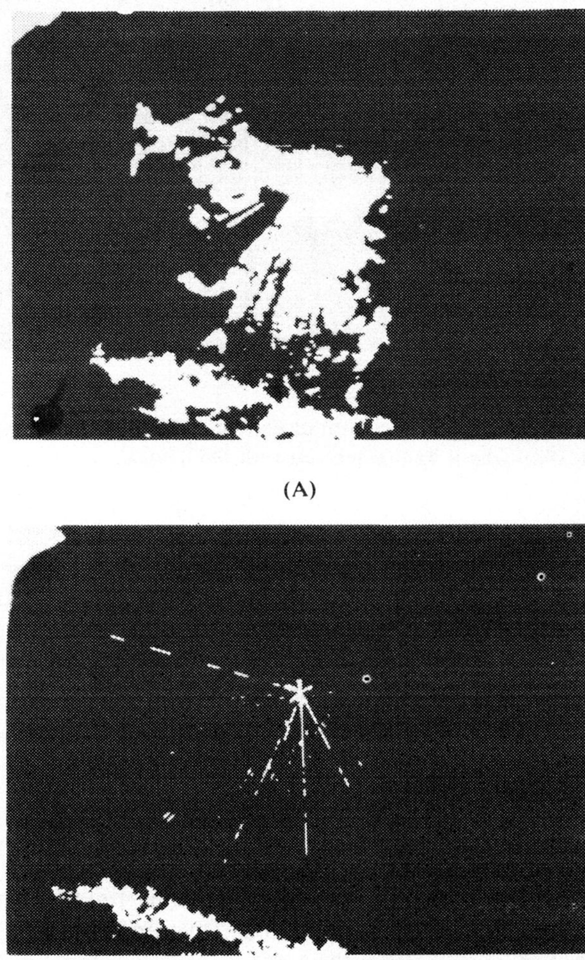

Fig. 7. PPI display of area around Florence with maximum range of 20 nm. (A) without MTI filter. (B) with MTI filter.

ture of the equalizer is to possibly introduce unwanted signals into distance-contiguous range bins, in case of nonperfect delay line equalization, leaving unaltered the transversal MTI filter performance with respect to radar echoes from the same range cell at subsequent sweeps. However, according to the results of the compensation technique sensitivity analysis, these unwanted effects can be made negligible.

A Reticon SAD 1024 device was used for the two CTD delay lines of the filter of Fig. 4, for which $N = 256$. This CTD delay line is not the best choice for radar applications due to its inherent low sampling frequency. However, its relatively high transfer inefficiency and its immediate availability allowed us to test the proposed method of CTI compensation. Fig. 5 shows the measured frequency response of the realized MTI filter with a sampling period $T = 2\ \mu s$, and Fig. 6 shows an example of the filter input and output signals. The input waveform simulates a moving target echo with a Doppler frequency equal to half the PRF embedded in a clutter return signal extended to several range bins. The output waveform clearly retains only the moving target signal component. The achieved MTI filter cancellation ratio was about 56 dB.

Tests in an operating environment were carried out including this filter in a radar system (SMA APS-705) of the noncoherent type. Figs. 7 and 8 show the plan-position indicator (PPI) displays without (Figs. 7(A) and 8(A)) and with (Figs. 7(B) and 8(B)) the second-order CTD MTI filter for two different maximum ranges. The straight lines in Fig. 7(B) are derived from echoes coming from adjacent radars that were operating on slightly different carrier frequencies at the moment the test was performed. The straight lines are not present in Fig.

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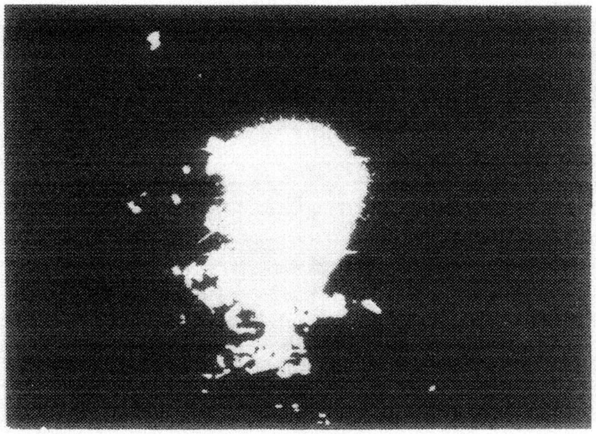
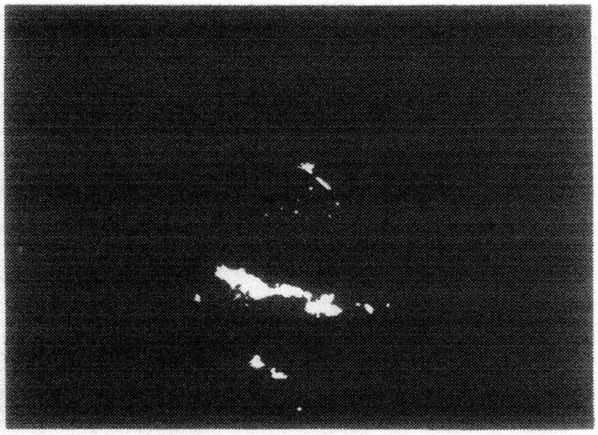


(A)



(B)

Fig. 8. PPI display of area around Florence with maximum range of 40 nm. (A) without MTI filter. (B) with MTI filter.

8(B) because the test was performed at a different time. In these tests the sampling interval was $T = 1.2\ \mu s$. At this clock rate the value of the product $N\varepsilon$ was 1/7. Even though this value is comparable with unity the compensated MTI filter attained a good clutter rejection as demonstrated by Figs. 7 and 8, where the retained echoes correspond to the moving clouds of a windy day.

IV. CONCLUSIONS

A second-order transversal MTI filter based on the use of commercially available CTD delay lines has been described. The filter includes specific compensation networks for eliminating the effects of the device CTI, which otherwise would greatly reduce the MTI filter performance. In particular the CTI compensation allows the second-order MTI canceler to be realized by the compact structure of Fig. 1 instead of two cascaded first-order cancelers. Actually the solution of Fig. 1 without CTI compensation would be unfeasible because of its greater sensitivity to the CTD CTI.

An attractive property of the structure of Fig. 1 is that, by changing the weighting coefficients in (1), complex zeros can be synthesized instead of two real coincident ones at $z = 1$. Therefore a wider clutter rejection region can be obtained by positioning complex zeros around the point $z = 1$.

Experimental tests carried out in both a laboratory and an operating radar environment have shown the good performance achieved by the CTI-compensated CTD second-order MTI filter. Further specific features of this filter are a low power consumption, small physical dimensions and weight,and the ease of changing the sampling rate, which allows the filter to be used in radars employing staggered PRFs.

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STEFANO BOZZI
UMBERTO CAPIGATTI
VITO CAPPELLINI
ENRICO DEL RE
MARCO MARGHERI
Istituto di Elettronica
Univezsità di Firenze
Via S. Marta 3
50139 Firenze, Italy

IVAN SALTINI
SMA, Firenze, Italy

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