

# Experimental Wideband Multi-Channel Cancellation Performance

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## ABSTRACT

For future radars with a wideband capability, effective electronic protection algorithms are required to perform target detection and discrimination. The Radar Division of Naval Research Laboratory has developed a flexible, adaptive wideband (400 MHz) multi-channel digital receiver/canceller test bed to investigate a radar's capability to reject interference. The effects of varied inter-channel hardware mismatches and intra-channel analog-to-digital aliasing on wideband cancellation performance are investigated. It is found that 23 dB of self-cancellation can be achieved with a proper combination of receiver implementation and cancellation configuration.

## 1. INTRODUCTION

Future radars with a wide instantaneous bandwidth will have to perform the tasks of target detection and discrimination in a wideband-interference environment. Effective electronic protection (EP) algorithms are required to defeat existing wideband interference. In the past, the performance of adaptive digital cancellers has demonstrated more than 25 dB of interference cancellation for narrowband radars with a 1 MHz bandwidth. Little experimental investigation exists on the radar's capability to reject significant interference over a much wider bandwidth.

To this end, the Radar Division of Naval Research Laboratory has developed a flexible, adaptive wideband (400 MHz at S-band) multi-channel digital receiver/canceller test bed. The canceller weighting is linear, digital, and adaptive. The test bed was operated in the self-cancellation (or calibration) mode, which is a first step in evaluating wideband cancellation performance. The difficulty of achieving effective cancellation over a wide bandwidth comes from the many and varied inter-channel hardware mismatches (such as the frequency response) and the intra-channel analog-to-digital (A/D) aliasing over the wide bandwidth. In this paper, the cancellation performance among multiple channels of the wideband data using various canceller algorithms was evaluated. Several parameters affecting the canceller performance were identified, and the means to achieve improved performance were investigated.

## 2. WIDEBAND MULTI-CHANNEL RECEIVER/ CANCELLER TEST BED DESCRIPTION

For the wideband test bed, the hardware used to capture the data across multiple channels consists of an analog receiver and an analog-to-digital (A/D) board (Echotek ECAD-2-081500) for each channel. The analog receiver, shown in Fig. 1 for a single channel, is a double-conversion receiver. The input can support frequencies from 1.2 GHz to 3.3 GHz. For this experiment, a 400 MHz wide input filter centered at 3.2 GHz was used. The receiver first mixes the RF input up to the 1<sup>st</sup> intermediate frequency (IF) with center frequency of 8.7 GHz using a tunable local oscillator (LO), and then mixes down to the 750 MHz output 2<sup>nd</sup> IF center frequency. Further filtering is performed to clean up the signal during the mixing processes. The analog output is an intermediate frequency (IF) signal, centered at 750 MHz and with a bandwidth slightly in excess of 400 MHz.

The analog-to-digital converter on the A/D board then samples the 2<sup>nd</sup> IF at 1 GHz and outputs 2 consecutive 8-bit samples at 500 MHz, in order to form simultaneous pairs of in-phase (*I*) and out-of-phase (*Q*) data components. These two data streams are then de-multiplexed to 8 channels each inside an Altera Stratix field programmable gate array (FPGA), for a total of sixteen 8-bit samples at 62.5 MHz. An external sync input to each A/D board is used to synchronize the de-multiplexing process across the multiple channels. These 16 bytes of data are then captured by a 2-Mbyte first-in-first-out (FIFO) memory. Since all of the A/D channels must be triggered simultaneously for this experiment, an external hardware trigger was generated for the A/D board to capture the data. The memory was configured to fill following an external trigger. The captured data was then unloaded across the VME backplane for further analysis (off-line processing). The ensuing digital data samples, sampled at a rate of 1 GHz which is four thirds of the IF center frequency and is greater than the Nyquist frequency of two times the analog bandwidth, represent a time series of alternating *I* and *Q* components. These components are then digitally filtered with tailored transversal filters (similar to those shown in [1]) to generate the desired simultaneous *I* and *Q* data pairs by the method of direct sampling. Four channels of *I* and *Q* data pairs are available as inputs to the cancellers. The canceller configurations are described in next section.

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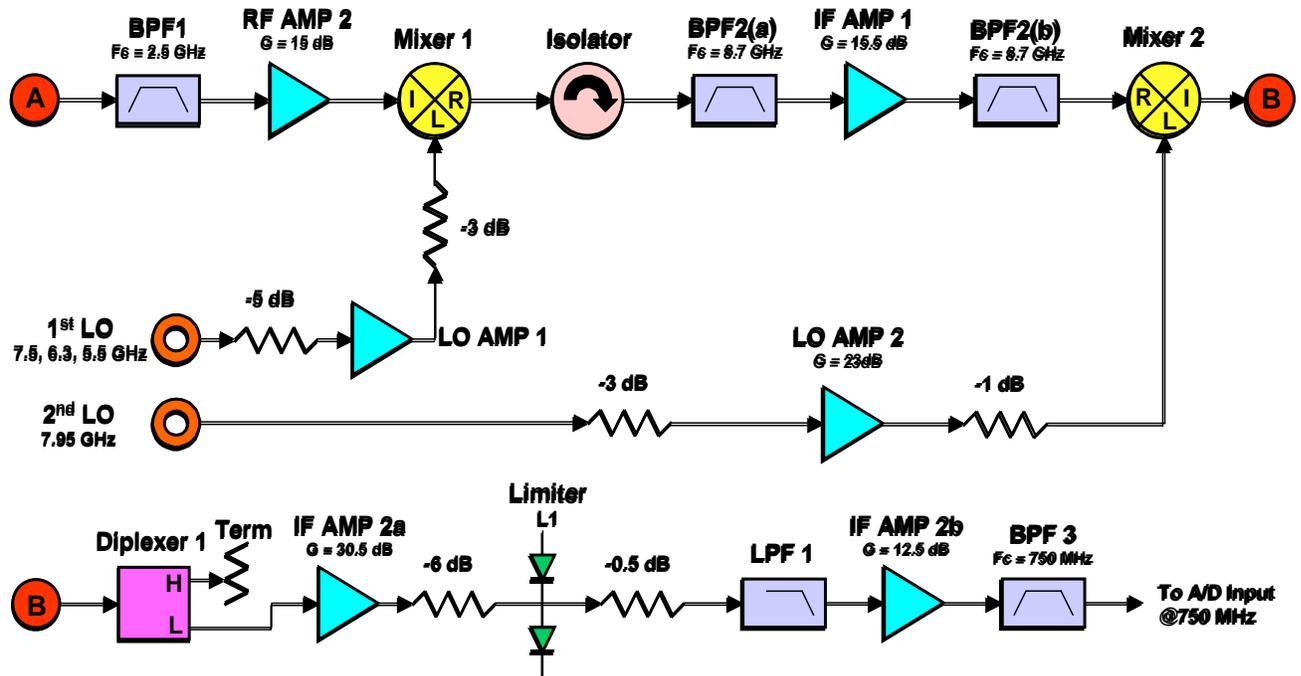


Fig. 1. Single-channel wideband receiver block diagram

### 3. CANCELLER CONFIGURATIONS

The canceller configurations chosen for the study are a 2-channel transversal filter canceller (TFC) [2] and a 2-channel band-partitioning canceller (BPC) [3,4]. In this paper, non-concurrent processing is used where the weights are determined first from a training data set, and subsequently applied to another data stream. The main channel weighting is constrained to equal one. The cancellation performance is measured by the cancellation ratio (CR), which is defined as the ratio of the before-cancellation main-channel power to the after-cancellation main-channel power.

The TFC is shown in Fig. 2(a). For this configuration, the auxiliary channel employs tapped delay-line compensation involving  $L$  weights and  $L-1$  delay elements of  $T$  seconds each, where  $T$  is the time between samples. A delay element of  $D = (L-1)T/2$  is included in the main channel, so that the center tap of the auxiliary channel corresponds to the output of the delay  $D$  in the main channel. Define  $\mathbf{w} = (w_1, w_2, \dots, w_L)^T$  to be the complex valued weighting vector, where  $T$  denotes the transpose operation. It can be shown [2] that to minimize the average output residue,  $\mathbf{w}$  is the solution of the vector equation  $\mathbf{R}\mathbf{w} = \mathbf{r}$ , where  $\mathbf{R}$  is the covariance matrix of the time-delayed taps in the auxiliary channel, and  $\mathbf{r}$  is the cross covariance vector between the auxiliary taps and the time-centered main channel. In practices,  $\mathbf{R}$ ,  $\mathbf{r}$ , and  $\mathbf{w}$  are estimated from the training data. The minimum residue signal power of a new data stream can then be obtained by applying  $\mathbf{w}$  to the auxiliary delay-line tap inputs and subtracting from the main-channel signal with delay  $D$ .

The BPC is shown in Fig. 2(b). For this configuration, the radar bandwidth is partitioned into subbands by using an

$N$ -point FFT, possibly weighted to reduce frequency sidelobe levels. The cancellation is performed within each subband using the weights developed from the training data set for each module  $C$ . The basic module  $C$  for the digital system consists of the open-loop canceller with two inputs. It computes the optimum weight based on averaging of the correlation between the input signals in the module's main ( $y_i$ ) and auxiliary ( $x_i$ ) channels of the training data [3,4]. The adaptive canceller weight  $W_i$  is given by

$$W_i = \frac{\overline{y_i x_i^*}}{\overline{x_i x_i^*}}$$

where  $*$  denotes conjugation, and the bar denotes averaging which is performed using a finite number of time samples in the main and auxiliary channels. For a new stream of data, the minimum residue  $r_i$  within each subband is obtained by applying the above optimum weight  $W_i$  multiplied by the auxiliary-channel signal and subtracting from the main-channel signal. Finally, taking the inverse de-weighted FFT of the residues of the  $N$  subbands produces a stream of residue signal.

For both canceller configurations, output residue power is determined using both complex weights and real weights for cancellation. The complex weights are developed when the inputs from the main and auxiliary channels are complex numbers  $I + jQ$ , where  $j = \sqrt{-1}$ . When complex weighting is used,  $I$ ,  $Q$  channel mismatch errors can result in cancellation degradation [5]. In a real-weight canceller [6], however, the weights are individually developed for the  $I$  and  $Q$  components of the inputs to the main and auxiliary channels.

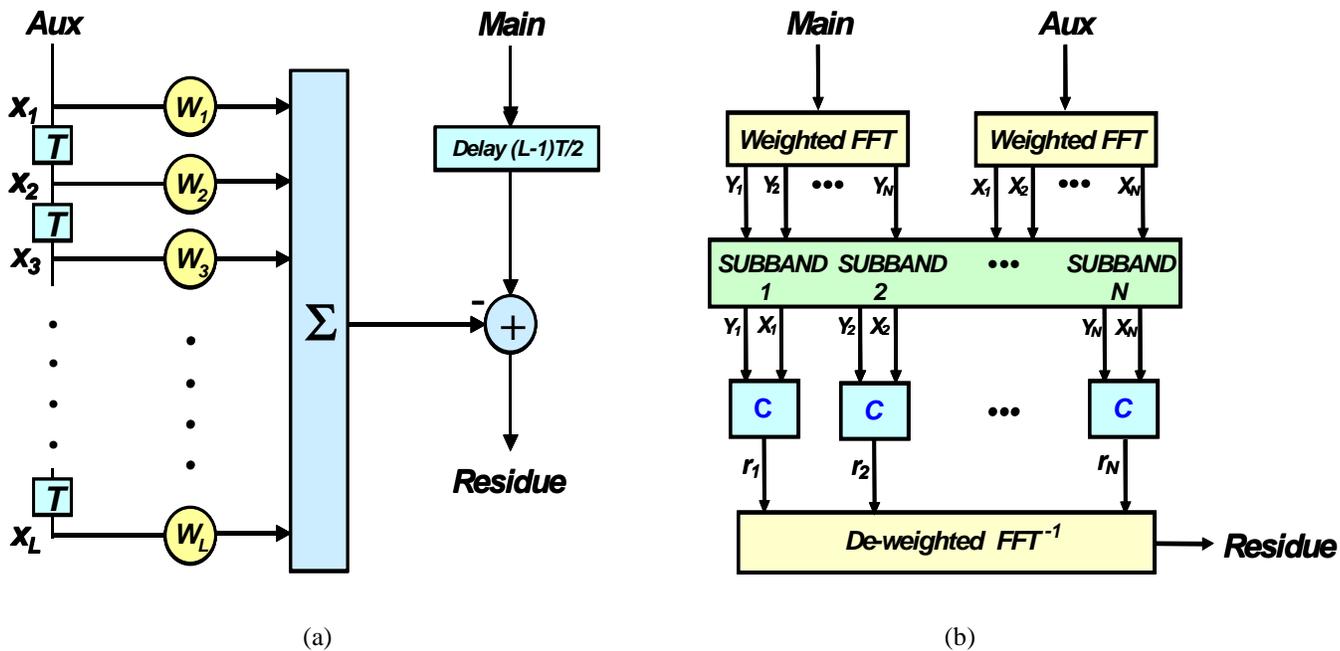


Fig. 2. Canceller configurations: (a) transversal filtering canceller, (b) band-partitioning canceller

#### 4. EXPERIMENTAL RESULTS

Several experimental tests were performed using the test bed with various receiver implementations. Both the unfiltered and the pre-filtered data were generated. For the unfiltered case, the data were input to the multi-channel receiver without any filtering. For the pre-filtered case, the data were pre-filtered with an analog filter with a sharp frequency cut-off response before being input to the receiver. Among the four-channel simultaneous *I* and *Q* wideband data pairs obtained by direct sampling method [1], only two channels of data were used at a time as the main and auxiliary channel inputs to the TFC and BPC configurations. The cancellation performance of these two configurations employing both complex and real weights was evaluated. The results of these experimental tests are presented in the following sections.

##### 4.1 Experimental Test 1: Unfiltered Data

In the first experimental test using unfiltered data, a stream of 4-channel simultaneous *I* and *Q* data was first generated from the real data. For each canceller configuration, only two channels of data were considered: one as main channel input and the other as auxiliary channel input. The cancellation performance was found to be similar for any two channels chosen. In a typical example, the power spectra of the input and the residues obtained after cancellation with complex weights for TFC with 63 taps and BPC with 64 subbands, are shown in Fig.3. Note that the power spectra of the input and the residues obtained after cancellation with complex weights for TFC with 63 taps and BPC with 64 subbands, are shown in Fig.3. Note that the power spectra were generated by the Welch method of spectral estimation

using FFT of length 256. The spectra extend over 500 MHz in frequency. Each sample number shown in the figure covers 1.953 (or 500/256) MHz in frequency.

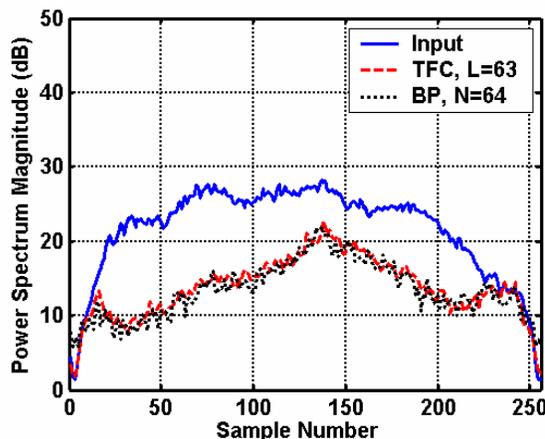


Fig. 3. Input and output residue spectra of the unfiltered complex data in the 1<sup>st</sup> experimental test for the 63-tap TFC and the 64-subband BP using complex weights

The residue spectra were quite similar for the two types of canceller configurations. The CR was found to be relatively small and only slightly improved if the number of taps was increased in TFC or if the number of subbands was increased in BPC. Similar results were also obtained if real weights were used.

The small CR obtained may be caused by the intra-channel A/D aliasing. As stated in the sampling theory, in order to preserve information, a signal must be sampled at or above the Nyquist rate. This is true for ideal band-limited signals, which possess no frequency components outside the stated bandwidth. In real systems, however, significant frequency components can exist outside the stated bandwidth. If such a signal is sampled at or above the Nyquist rate, aliasing may result and the high-frequency components of the signal are folded back and added to the low-frequency components. One way to mitigate the aliasing problem is to pre-filter the signal. This was accomplished in the second experimental test.

#### 4.2 Experimental Test 2: Unfiltered and 400-MHz Pre-Filtered Data

In the second experimental test, both the unfiltered data and the data pre-filtered with an analog filter of 400-MHz bandwidth were obtained. The cancellation performance of the pre-filtered complex data exhibited approximately a 6-dB improvement over the unfiltered case, indicating that the A/D aliasing problem was abated. The magnitude of the power spectrum for the input data and the residue obtained after cancellation for a TFC with 63 taps, with both complex and real weights applied, is shown in Fig. 4. The sample number used here is the same as that used in Fig. 3. The output residue seemed to be suppressed at both ends of the spectrum for TFC applying real weights as compared with complex weights. Consequently about a 4-dB CR improvement with the real-weight canceller over the complex-weight canceller was observed. In theory, the real-weight canceller would provide almost optimum cancellation, even in the situation when lack of quadrature between the  $I$  and  $Q$  components of the output of the radar receivers exists. Consequently, the canceller using real weights is more effective than the complex-weight canceller, making the canceller performance responsive to compensation with a transversal filter. The corresponding power spectrum for a BPC with 32 subbands using complex weights was also obtained. The CR was comparable to the case of a TFC using complex weights. For a BPC using real weights, however, improvement in the CR was not observed.

The effects of increasing the number of taps  $L$  in TFC have also been investigated. The performance of the TFC, with the pre-filtered complex data applying both complex and real weights, was obtained. As shown in Fig. 5, the CR increases more rapidly with the increasing  $L$  when  $L$  is small. For larger values of  $L$ , however, the CR approaches a steady state value. There is a 4 to 5 dB of CR improvement for the real-weight canceller over the complex-weight canceller when  $L$  is greater than 15.

Finally, the performance of the TFC for the pre-filtered data stream, derived without direct sampling (direct sampling could be applied to the output after cancellation to obtain  $I$  and  $Q$ ), was also obtained as number of taps increased. In Fig. 5, for large number of taps, the “real-data” CR surpasses that achievable with the real-weight canceller using the complex input data.

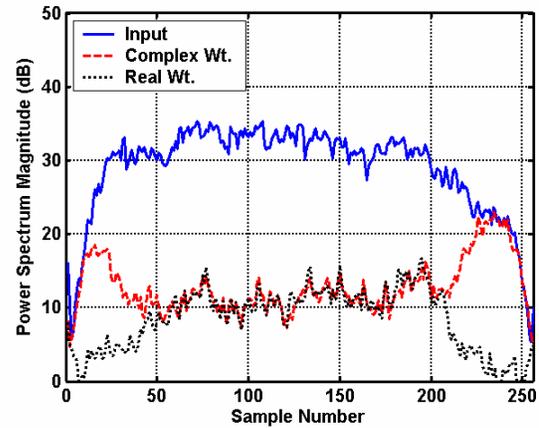


Fig. 4. Input and residue spectra of the pre-filtered complex data in the 2<sup>nd</sup> experimental test for the 63-tap TFC using complex and real weights

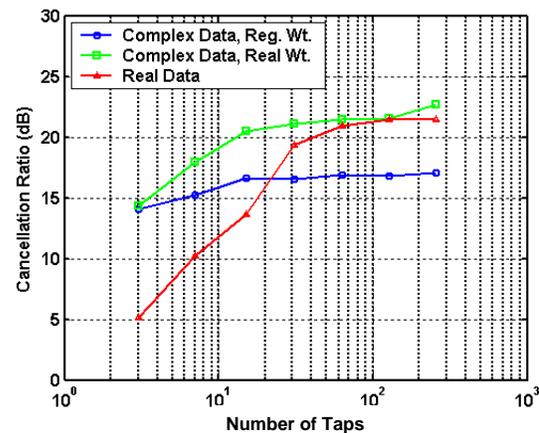


Fig. 5. Cancellation performance of the pre-filtered data in the 2<sup>nd</sup> experimental test for a TFC vs. number of taps: complex data using complex and real weights, and real data using real weights

#### 4.3 Experimental Test 3: Unfiltered and 200-MHz 200-MHz Pre-Filtered Data

The high level of output spectrum at both ends shown in Fig. 4 might be due to the  $I$  and  $Q$  channel mismatches. Using the real-weight TFC, as demonstrated in the Experimental Test 2, reduced these mismatches. It seemed reasonable that applying an analog filter with a narrower bandwidth than the 400 MHz could suppress the residues at both ends of the output spectrum. In the third experimental test, an analog filter with a bandwidth of 200 MHz was used for pre-filtering.

Both filtered and unfiltered data were collected. The cancellation performance versus number of taps in the TFC using complex and real weights for both data sets is shown in Fig. 6. Applying both types of weights yielded similar results for the TFC, implying that the  $I, Q$  inter-channel mismatch

was reduced using a narrower bandwidth for pre-filtering. Only slight CR improvement was observed as the number of taps increased. As compared to the second experimental test, the CR for smaller number of taps was much higher for the complex data with a 200 MHz than a 400 MHz pre-filtering bandwidth; the CR for larger number of taps, generally about a 5-dB performance enhancement was observed. Moreover, the performance was comparable when the unfiltered data were used.

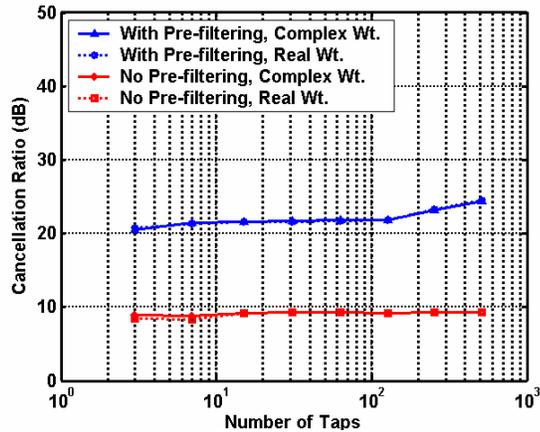


Fig. 6. Cancellation performance of a TFC vs number of taps for the 3<sup>rd</sup> experimental test pre-filtered and un-filtered data with complex and real weights

To study the effects of bandwidth on the cancellation performance, a digital-filtering operation was applied to the pre-filtered data in the third experimental test to reduce the bandwidth. Figure 7 shows the input power, residue power, and the CR for a TFC with 63 taps as the data bandwidth was reduced to fractions of its original bandwidth. For very narrow bandwidths, the residue output power was reduced to the noise level, as expected for narrowband case. Similar results were also found for a BPC with 64 subbands.

### 5. CONCLUSIONS

Effective EP algorithms are required to perform target detection and discrimination for future radars operating with wide instantaneous bandwidth. In order to develop effective EP algorithms against current and future interference, the Radar Division of Naval Research Laboratory has developed an experimental test bed consisting of a flexible, adaptive wideband multi-channel digital receiver/canceller. As a major step toward developing capability against the interference, it is necessary to demonstrate that the wideband channels of a multi-channel receiver can be calibrated or balanced to a significant level of exactness. Via the test bed, multi-channel receiver data was digitally recorded and thereafter used to evaluate the performance of various wideband canceller algorithms.

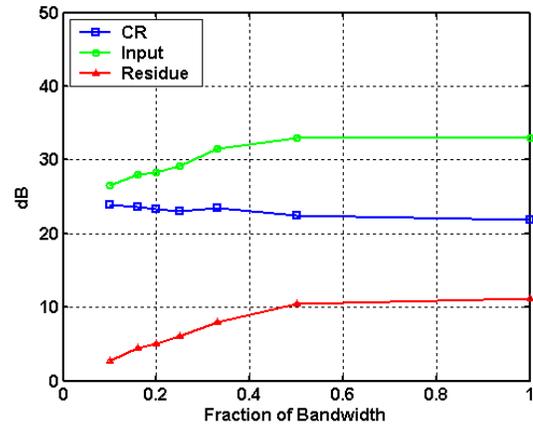


Fig. 7. Performance of a TFC with 63 taps, input and residue power for the 3<sup>rd</sup> experimental test pre-filtered data with digital filtering to reduce bandwidth

The effects of many and varied inter-channel hardware mismatches and intra-channel analog-to-digital aliasing on the wideband cancellation performance were investigated. It was found via the test bed with proper receiver filtering and canceller configuration, that channel calibration of  $-23$  dB over 400 MHz was achieved, which would support 23 dB of interference cancellation. The enabling technology developed from the wideband cancellation experiments presented here will be a step forward for identifying effective canceller configuration and receiver implementation of future wideband radars against the interference.

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