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High Dynamic Range Nonlinear Measurement using Analog Cancellation

by Joshua M. Wetherington and Gregory J. Mazzaro

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Joshua M. Wetherington and Gregory J. Mazzaro
Sensors and Electron Devices Directorate, ARL

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An active analog canceller system is implemented to maximize the dynamic range of a two-tone nonlinear measurement, a common test for nonlinear radio frequency behavior. The canceller uses active feedforward cancellation, controlled by a fully automated iterative algorithm. The system enables testing of a variety of nonlinear channels and devices, either by direct connection or wireless probing. In this report, the advantages of feedforward cancellation are summarized, a two-tone architecture using this cancellation is presented, the software algorithm for automating measurements using this architecture is explained, and the performance of the cancellation system recently constructed at the U.S. Army Research Laboratory (ARL) is evaluated using measured data.

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Contents

List of Figures

List of Tables

1. Introduction

1.1 High Dynamic Range Nonlinear Measurement

Modern receivers with very high sensitivity are plagued by the generation of low power distortion products that appear within the receiver bandwidth. These distortion products are the result of interference of a high-power signal on weakly nonlinear paths, typically leakage from a transmitter, also known as passive intermodulation (PIM) distortion. Elimination of this distortion is essential to avoid degradation in high performance radios or very sensitive electromagnetic probing applications.

It is very difficult to characterize the weakly nonlinear channel or target, because the dynamic range of the high-power interferer to the very low-power distortion products is beyond the limit of common laboratory equipment. Usually the high-power excitation signal needed to generate passive distortion products saturates the receiver, preventing any low-level detection. It is desirable to remove the high-power signal after distortion generation in the target, but before detection.

In this system, analog cancellation is implemented to improve the dynamic range for two-tone nonlinear measurement, one of the most common tests for nonlinear radio frequency (RF) device behavior. The canceller uses active, feedforward cancellation controlled by a fully automated and efficient cancellation algorithm. The system has been developed with enough generality to enable testing of any nonlinear channel or device, either through a direct conducted path or with wireless probing. Implementation of the cancellation system at the U.S. Army Research Laboratory (ARL) is intended to extend the continuous-wave harmonic and switched-tone intermodulation results presented in reference 1 and 2 to two-tone intermodulation responses recorded from similar RF devices.

1.2 Feedforward Cancellation

In an analog canceller, two signals are combined such that they destructively interfere, resulting in a net decrease of signal amplitude, or signal cancellation. A typical analog canceller architecture using a feedforward signal to cancel a probing signal is shown in figure 1.

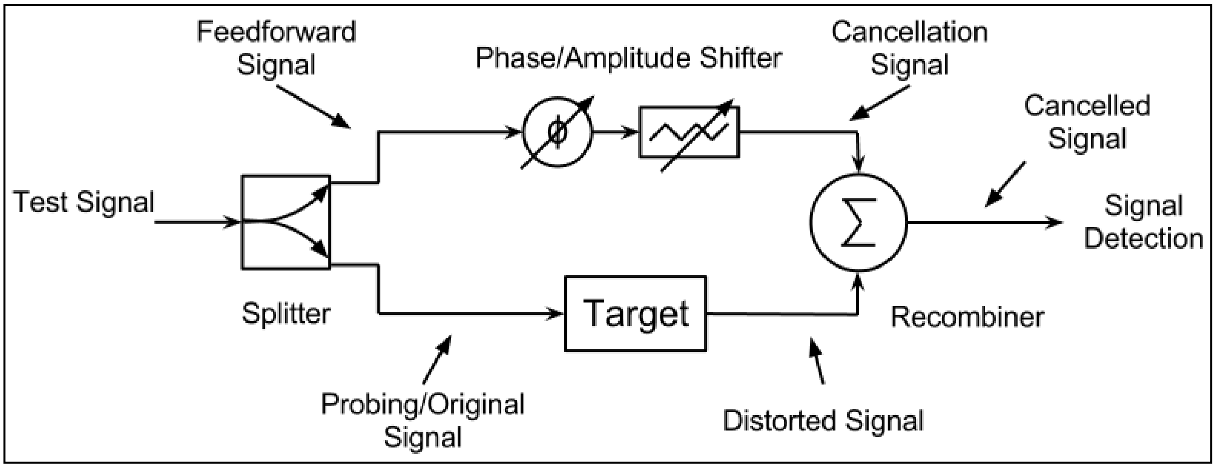

Figure 1. Analog canceller architecture.

The phase and amplitude shifters on the cancellation path allow for manipulation of the feedforward signal to maximize cancellation. For equal frequency sinusoids, total cancellation strictly occurs only for two ideal signals equal in amplitude and 180° out of phase. In a real system, the achievable cancellation is limited to

$$C_{dB} = -10\log\left[1+\varepsilon_{\alpha}^{2}-2\cos\left(\varepsilon_{\phi}\right)\right] \quad (1)$$

where ε_α is the linear amplitude imbalance and ε_ϕ is the phase error from 180° out-of-phase of the two signals (*3*).

Using trigonometry, the phase offset between two combined tones is determined using only signal amplitude measurements. The applied phase shift ϕ needed for complete cancellation is calculated as

$$\phi = \pi \pm \arccos\left(\frac{\beta}{2\alpha}\right) \quad (2)$$

where α is the amplitude of the individual signals (assumed to be equal) and β is the amplitude after combination (*3*). The ambiguity of the sign is resolved by taking a second combined signal amplitude measurement after adding a known phase shift to one of the tones.

1.3 Advantages of Feedforward Cancellation for Nonlinear Detection

In a typical nonlinear measurement system, filtering is used to remove the high-power interferer to enable low-level nonlinear detection. Filter-based systems are limited by the tunability and finite roll-off of filter passbands. Few filters currently enable automated broadband tuning while maintaining a high Q-factor and minimal loss. Filter banks may be substituted, but the large number of filters is often cost-prohibitive. In addition, no filter can provide attenuation of the interferer without also attenuating nonlinear signals very close in frequency. Even minimal loss on the edge of the stopband is enough to drive low-level products below the sensitivity of the system. New systems based on tightly designed resonators further exaggerate these complications (*4*).

The use of an analog canceller addresses most of these issues. The analog canceller achieves both a broadband automatic tuning capability and extremely high Q-factor by canceling the high-power interferer with a sampled version of itself. By removing the highly frequency-dependent filters, the bandwidth of the system is limited only by the remaining components in the system, e.g., power amplifiers and power combiners, which usually have very wide bandwidths. Unlike the filters, only the high-power probing signal is attenuated, since the distortion products do not exist in the feedforward signal, enabling measurement of nonlinear products separated in frequency from the probing signal by a minimum of 1 Hz. With adequate cancellation, distortion in the same bandwidth as the test signal is observed (*5*).

As an active system, the analog canceller suffers some disadvantages. The extended architecture required in both hardware and software adds significant complexity and is inherently slower than passive filter-based systems. This complexity also reduces the performance of the system, since low level detection is heavily dependent on achieving sufficient cancellation depth, requiring precise calibration and tuning. The active devices, needed for both manipulation of the feedforward signal and amplification of the probing signal, are highly nonlinear and contribute significant levels of noise and spurious interference. By avoiding the use of filters, it is more difficult to remove any spurious signals and extra care must be taken to prevent their generation.

2. Two-tone High Dynamic Range Architecture

2.1 System Design

The single-channel analog canceller in figure 1 is extended to a full two-tone measurement system using two separate channels, as shown in figure 2. Two configurations are shown for the target: transmission measurement for two-port targets and reflection measurement for one-port targets. Either configuration supports a wireless channel, using two separate antennas for the transmission measurement or a single antenna for the reflection measurement. For best performance, the target configuration used should be hard-wired instead of switched as shown.

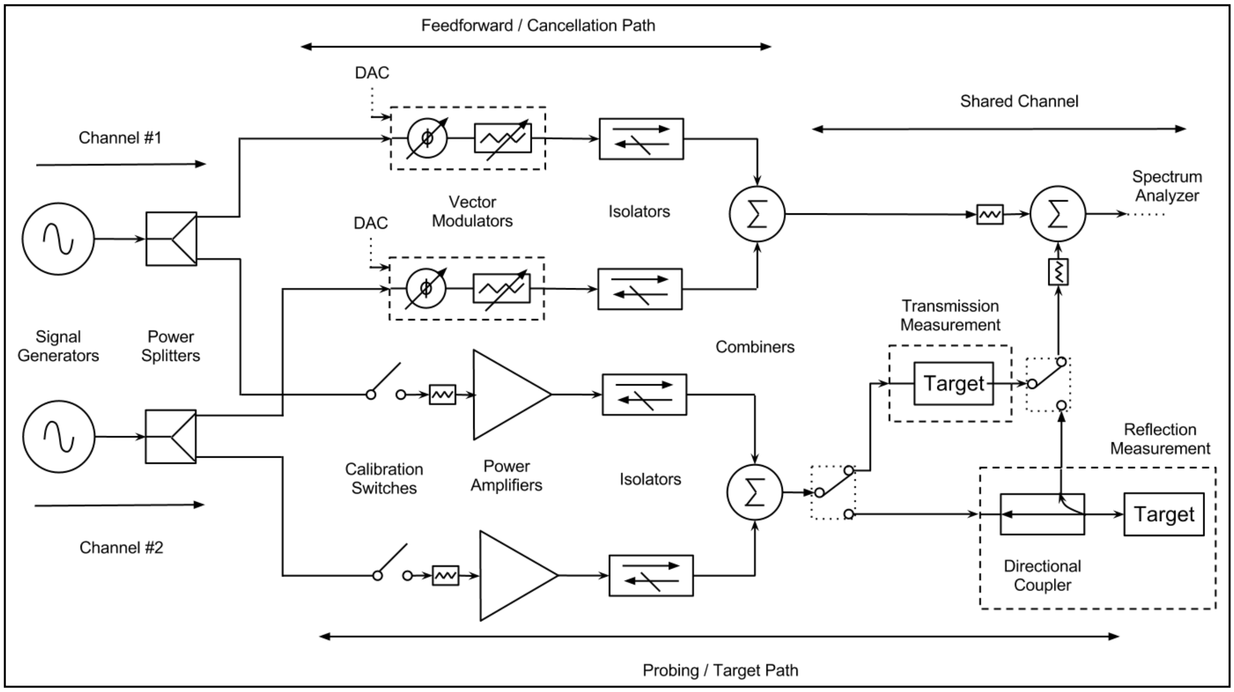

Figure 2. High dynamic range two channel (two-tone) architecture.

The vector modulators allow for digital control of the amplitude and phase of the feedforward signal of each channel by modifying the I and Q inputs with a digital-to-analog converter (DAC). Since the cancellation limit (equation 1) relies on both amplitude and phase accuracy, the analog output resolution of the DAC provides a rough estimate of the maximum theoretical cancellation possible on each channel. Conversion gain, attenuation, and other factors also affect the accuracy of the vector modulator output, changing the maximum limit accordingly. In the implemented system, Hittite HMC497LP4 vector modulators are used with Measurement Computing USB-3103 16-bit DACs, which should theoretically allow over 60 dB in cancellation. Nearly 80 dB has been demonstrated in the implemented system, and up to 90 dB has been demonstrated in an identical system (*3*). Switches on the stimulus path allow the vector modulator outputs to be calibrated without interference from the high-power test signals at the recombination point (further discussed in section 3.2).

2.2 System Intermodulation and Noise Suppression

Isolated channels for each tone are necessary to minimize system intermodulation product generation. The power amplifiers, used for boosting the power of the probing signal, and the vector modulators are both highly nonlinear active devices. Any cross-channel coupling of the test tones results in intermodulation generation that may greatly exceed the PIM generated in the target, limiting detection sensitivity. The largest sources of cross-channel coupling are reverse leakage at the combination points and radiated coupling.

Isolators or circulators are used to prevent reverse leakage of opposite channel tones through the combiners. At least 30–40 dB of reverse isolation is recommended to completely minimize measurable intermodulation from the power amplifiers, usually 2–3 isolators. The intermodulation generated in the vector modulators is often much less than the amplifiers, although reflections may impact the linearity of the feedforward signal phase, complicating cancellation. At least 10–20 dB of reverse isolation is recommended after the vector modulators. The isolators also exhibit highly nonlinear behavior as ferromagnetic components but the generated intermodulation products are generally at or below the noise floor with no reflections from the target. In construction of the system, Raditek circulators (RADC-650-1000M-N23-100WR-b) were used.

Radiated coupling may occur between any two cables in the system. Cables on the high-power path (after the power amplifiers) are most likely to radiate, while cables before the active devices are the most sensitive. Shielded cable is essential, and cable lengths should be kept to a minimum. Any cabling between the power amplifiers and target should be eliminated, if possible. Copper mesh and copper tubing is used to create a secondary shield around sensitive areas. The target may also be sensitive to radiated coupling from the system and will benefit from a shield box or Faraday cage, if it is not already enclosed.

On the shared measurement path and through the target, cross-channel coupling cannot be prevented, so low-PIM components should be used to ensure that target nonlinear generation is measurable above system levels. In general, components with low PIM benefit from large physical size and distributed structures. DIN- or N-type connectors with silver plating have been shown to produce the lowest levels of intermodulation (*6*). In highly sensitive paths, extremely long cables may be used as attenuators and terminations, and produce no significant levels of PIM (*3*).

2.3 Spurious Noise Suppression

Primary sources of spurious noise (spurs) in the system include the test signal source and line noise in the active devices. External spurs may also arise in a laboratory environment due to uncontrolled emissions, especially when using a nonlinear target in a wireless test. Interference from external sources must be shielded against, but it is often impractical or impossible to shield spurious tones arising within the system.

Spurs originating in the signal source are coupled to the feedforward path along with the fundamental tone. This noise is correlated with the noise of the main probing signal, so cancellation at the recombination point causes a reduction or elimination of source spurs. Noise generated independently on the individual paths is random with respect to the opposite path and instead sum at the output. The excess path noise does not usually limit the sensitivity of the measurement.

For measurements using very low frequency separations of less than 1 kHz, noise introduced by the 60-Hz power line may produce significant interference. Due to poor internal power supply rejection in both the power amplifiers and vector modulators, both should be powered by extremely well-regulated linear DC supplies or preferably batteries. Switching DC supplies produce significant interference at harmonics of the switching frequency, while linear power supplies is limited to 60-Hz multiples. Line noise from the signal sources may also be significant, and DC-powered sources are preferred.

Most signal sources and power amplifiers are actively cooled using fans tied to the same power supply. Even on perfectly regulated DC power, the cooling fans may create reverse electromagnetic interference on the power line that is measurable at the output of the system. It is strongly advised to isolate the power supply of the cooling fans from the main power supply of the device using a separate DC supply if possible. In this case, proper controls must be maintained to ensure that the fans remain powered while the equipment is operating to avoid overheating and damage.

Harmonics of the test tones are currently a significant problem for the system. While the harmonics generated in the signal source are usually very low, the harmonics generated in the power amplifiers and vector modulators are extremely large, usually far exceeding the cancelled power of the probing signal. While many passive components in the system naturally filter harmonics due to limited bandwidth, especially the isolators, this is usually not sufficient for anything but active nonlinear targets. If harmonic testing is desired, traditional filtering is recommended, as the primary benefits of the analog canceller are effectively nullified.

2.4 Wideband Noise Floor

The system wideband noise floor is strongly dependant on the resolution bandwidth used by the spectrum analyzer. Optimally, 1-Hz resolution bandwidth is used (if supported) to minimize spectral thermal noise summation. Very low resolution bandwidth measurements greatly extend testing time, but are necessary to achieve the highest dynamic range. For the purposes of high-power signal cancellation, or for highly nonlinear targets, the resolution bandwidth may be increased to decrease test time, with a 10-dB increase in thermal noise for every tenfold increase in bandwidth.

Given an optimal resolution bandwidth, for a very small frequency separation of 100 Hz or less, the noise floor of the system is driven by the phase noise of the probing signal from the signal generator and digital processing of the signal. The phase noise always roughly maintains a fixed relationship to the fundamental signal, so improved cancellation also decreases the phase noise accordingly. Outside of the phase noise, the system noise floor is driven by wideband phase noise from the vector modulators. This phase noise may be improved by attenuating the signal, but this limits the maximum power output that may be used for cancellation (see section 2.6).

Even with attenuation, the noise floor cannot be reduced below the thermal noise level dictated by the resolution bandwidth.

2.5 Bandwidth

For a two-tone measurement system, there are two components to operating bandwidth: variation in center frequency of the tones and variation of the tone separation. Filters usually impose a small range on center frequency and frequency separation, with a high minimum frequency separation. The frequency separation of the two tones determines the frequency spacing of the intermodulation products, so frequency separation less than the minimum using filters results in undesired attenuation of the intermodulation products. In the analog canceller, bandwidth is primarily limited by the isolators or circulators, which may have bandwidths of up to an octave. This again limits the center frequency range and maximum frequency separation, but not the minimum frequency separation, allowing for frequency separations as low as the resolution bandwidth of the spectrum analyzer or the frequency step of the signal generators. In the implemented system, the intermodulation products of tones as close as 1 Hz apart are resolved. Isolators in different frequency bands may be used on each individual channel to allow for extended frequency operation, but lack of a common bandwidth restricts the minimum frequency separation. The remaining components in the system tend to have much wider continuous bandwidths of a decade or more, imposing no additional restrictions provided the bandwidth of interest is contained within the component's bandwidth.

2.6 Power Restrictions

Maximum power within the system plays an important part in limiting the dynamic range of the system. Higher power levels are desirable in order to drive the weak nonlinearities of the target to measurable. While low-PIM components often have high power ratings due to large, distributed structures, most common laboratory components are not designed for operation at 20 W, the industry standard test power. At a 1–2 W test signal power, enhanced dynamic range becomes even more important since intermodulation power falls much faster than the test signal power.

The power amplifiers used in the system are Mini-circuits ZHL-20 W-13+, with a maximum output power of 43 dBm (20 W), and 1-dB compression point of about 40 dBm (10 W). To ensure linearity, the amplifiers should be used at a much lower output than the 1-dB compression point. In the two-tone configuration in figure 2, due to the combiner and isolators between the target and amplifiers, there is an additional 3–5 dB of loss before the target. For the purpose of getting as much power to the target as possible, all unnecessary cabling between the amplifiers and target should be eliminated. This allows a maximum target power of roughly 30 dBm (1 W), with minor amplifier compression. To eliminate all significant compression, the target power should be no higher than 24–27 dBm.

In measurements where a majority of the target incident power is reflected or transmitted to the measurement path, extra attenuation may be necessary to ensure that the signal power is less than the maximum power of the feedforward signal. The extra loss also attenuates intermodulation products, so highly reflective or high transmission targets suffer from reduced dynamic range. The vector modulators output up to 8 dBm, but the feedforward signal must also pass through isolators and a combiner before cancelling the target signal. Adding additional loss after the vector modulator to reduce phase noise, as described previously, also limits the maximum power available for cancellation. Eliminating attenuation in the target and measurement paths should generally be favored over reducing phase noise from the vector modulators.

2.7 System Intermodulation Generation with High Reflectivity Targets

In the case of a well-matched target, the reflection of the high-power probing signal back into the system should be minimal. Combined with high reverse isolation from the isolators and good input isolation in the combiner, the cross-channel coupling reaching the power amplifiers via conducted paths should be small enough that the intermodulation products generated are not measurable at the output of the system. For a highly reflective target, such as an antenna, a majority of the signal power is returned, and significant levels of cross-channel coupling reach the power amplifiers. Assuming that intermodulation behavior is perfectly mirrored between the two channels, the reverse isolation provided by the isolators only reduces system intermodulation products generated by the amplifiers by a 1:1 relationship. Thus, even 30–40 dB of reverse isolation may result in significant levels of system intermodulation at the output. Additional isolation may sometimes help but the nonlinearities of the isolators also produce significant intermodulation, negating any benefit. The use of attenuators to improve isolation also tends to increase intermodulation, due to the need to drive the power amplifiers higher to produce the same power at the target. Ultimately, highly reflective targets reduce maximum achievable dynamic range, with the worst passive case being a perfect open or short. Active target loads should be treated very cautiously if measured on a direct, conducted path.

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3. Software Architecture

3.1 Automation

Using the phase shift equation (equation 1) and signal amplitude measurements at the receiver, the system is automated to acquire high levels of cancellation. To determine the required phase shift for the feedforward signal, a minimum of three separate measurements are needed. The individual signal amplitude, α, only needs to be measured once, since it is independent of feedforward phase. The combined signal amplitude, β, needs to be measured twice, to determine both the value of the phase shift, ϕ, and the proper sign. For a given level of cancellation at a reference phase, the appropriate phase of the feedforward signal may be either advanced or delayed. A measurement at a second reference phase, with a known shift from the first reference phase, is needed to find the correct direction, as illustrated in figure 3.

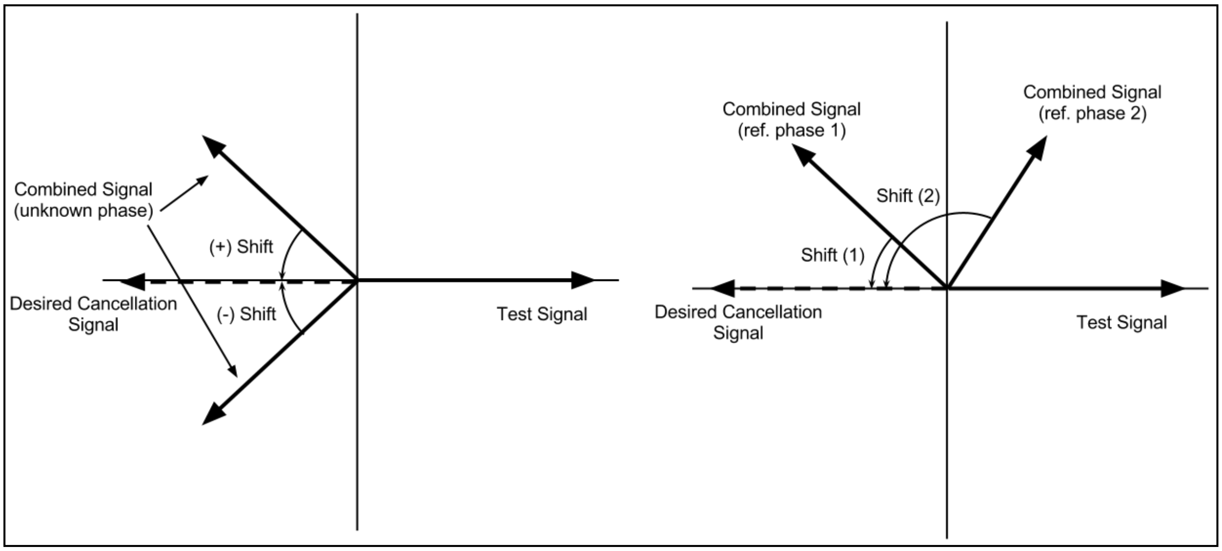

Figure 3. Using multiple measurements to resolve ambiguity of the phase shift equation.

3.2 Feedforward Signal Calibration

On an ideal, linear channel, applying the calculated phase shift to the feedforward signal should yield complete cancellation of the test signal. Non-idealities in the feedforward path introduce some error, limiting cancellation. These nonlinearities include digital control errors from quantization noise; time-dependant variation due to temperature, humidity, or battery depletion; and amplitude variation within the vector modulator.

The largest error currently introduced is variation of the vector modulator output amplitude over an applied phase shift. The magnitude of the amplitude error varies for each device sample. For best performance, a vector modulator with less than 0.3 dB of total amplitude swing over phase should be used. Vector modulators with a larger amplitude error swing may also suffer other defects and should be avoided. Cancellation with 0.3 dB of amplitude error is limited to 30 dB, so an additional corrective step is needed to calibrate the amplitude. The time-dependant variations previously mentioned compound this error, so the extra calibration must be in-line with the measurement procedure at the time of setting the vector modulator phase. The full cancellation procedure including the in-line calibration is shown in figure 4.

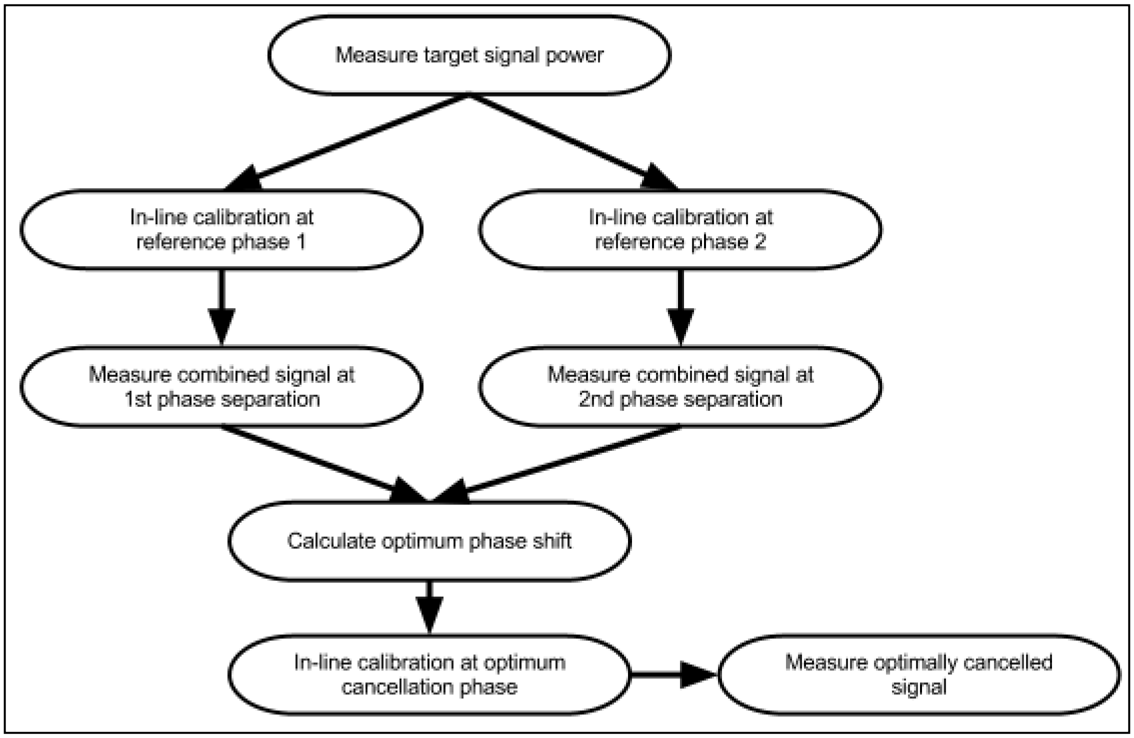

Figure 4. Procedural flow for a full feedforward cancellation measurement.

In the simplest form of in-line calibration, the feedforward signal amplitude is measured after setting the vector modulator for the appropriate shifts and disabling the probing signal path by opening the calibration switches (see figure 2). This amplitude is compared to the desired signal amplitude, and a linear shift is added to the vector modulator inputs to compensate for the amplitude error. Experimentally, this is often sufficient to improve the amplitude error to 0.01 dB or better for a vector modulator with an error amplitude swing of 0.3 dB or better. The in-line calibration is extended with a second amplitude measurement and linear interpolation to compensate vector modulators with a larger error amplitude swing. This calibration is applied each time a new phase is applied to the vector modulator, so the extra measurement is costly in time for overall procedure. More complex calibration schemes do not improve results, since the calibration is limited by measurement accuracy and time variation. The results of applying the in-line calibration to a feedforward signal varying over phase is seen in figure 5 for the vector modulator on each channel.

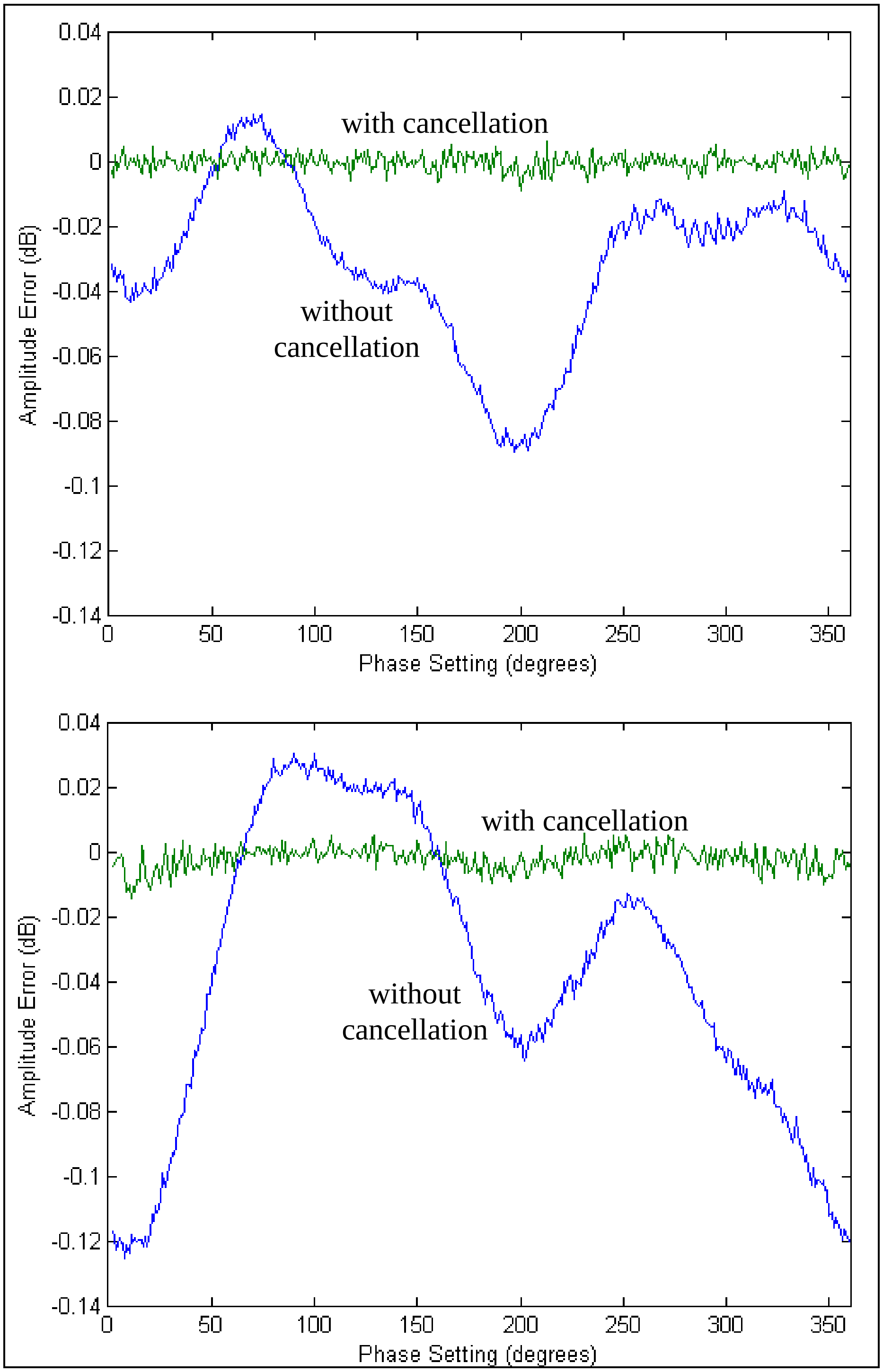

Figure 5. Sample phase-dependant data showing improvement with in-line calibration: (top) channel #1 and (bottom) channel #2.

3.3 Iteration

While amplitude calibration of the feedforward signal eliminates the largest source of cancellation error, in general, there exists some nonlinearity of the feedforward path and signal combination over phase. This nonlinearity leads to inaccurate estimates for the feedforward signal phase shift, again limiting cancellation, and becomes worse as signals become more in-phase. To maximize cancellation from any arbitrary phase offset between the feedforward and test signals, a weakly iterative technique is used. This method takes advantage of the improving relative nonlinearity as the signals approach 180° offset. In reference 3, iteration is achieved by looping through the full cancellation procedure, as shown in figure 4. Here, redundant measurements are removed to form a more aggressive iteration scheme with higher measurement efficiency, as shown in figure 6. Each successive iteration uses the combined signal amplitude of the previous two iterations to calculate the new feedforward signal phase shift. The calculated phase shift after the first iteration assumes a positive shift due to the lack of two previous measurements, so useful cancellation is not guaranteed to occur until the third iteration. With favorable initial conditions, sufficient cancellation may occur sooner. Note that the full cancellation procedure, as described in reference 3, is roughly equivalent to three iterations as described here.

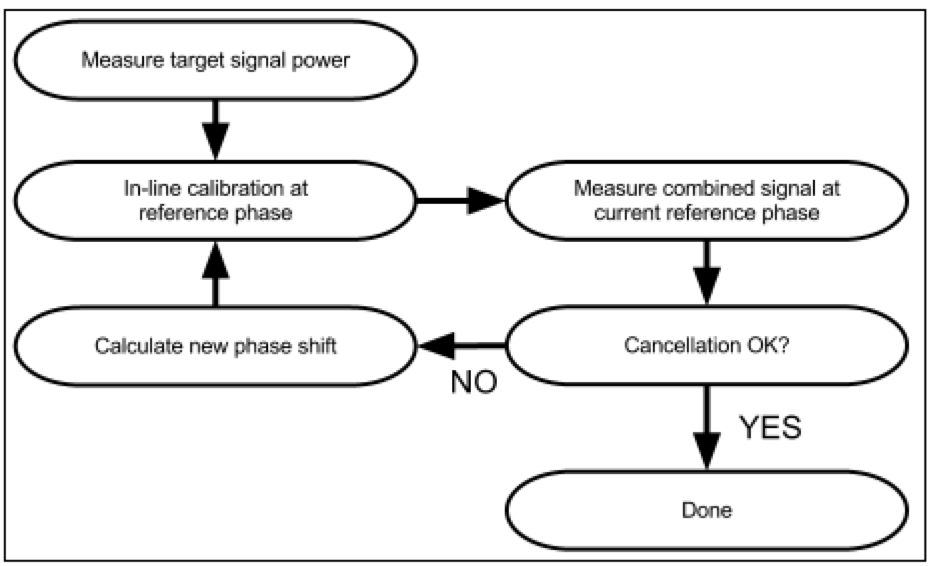

Figure 6. Procedural flow for iterative cancellation.

This iterative method is not strictly a mathematical iteration since the residual error is never used except for a binary decision to terminate. This allows for increased efficiency in finding the solution phase, since each iteration theoretically converges on ideal cancellation, given at least two iterations. A cancellation target, C_T, is required for the loop to terminate, so a loop counter should always be set to ensure stability. Statistics for one channel of the implemented system are given in table 1 for measured iterative cancellation using various values for C_T. Each cancellation target was swept over the full range of feedforward signal phase shifts from 0° to 360° in 1° increments to exhaust the full range of test conditions. For $C_T = 0$, one full cancellation procedure was forced to ensure useful cancellation. The cancellation statistics are similar to the ones reported in reference 3, but the iterations required have reduced slightly due to a more aggressive iterative procedure. The more aggressive procedure is much less robust for the higher cancellation targets, so meeting extreme cancellation requirements requires the slower, full iterative method.

Table 1. Canceller performance statistics.

	Iterations				**Measured Cancellation (dB)**			
C_T (dB)	**Average**	**Max**	**Median**	**σ**	**Average**	**Max**	**Min**	**σ**
0	3.00	3	3	0.00	43.1	74.4	13.3	14.1
30	2.98	5	3	0.82	49.1	75.9	30.1	10.6
50	3.74	19	4	1.62	63.2	78.8	50.1	7.0

4. Intermodulation Dynamic Range

Intermodulation dynamic range (DR_{IM}) is defined as the ratio of the target input signal power to the minimum detectable signal (MDS) at the intermodulation frequency (*3*). This measure combines the dynamic range of the receiver with the analog cancellation and signal suppression from the target to determine the range between the largest and smallest signals measurable in the system. The relationship between important power levels in the system and how they relate to dynamic range and losses is detailed in figure 7. Unfortunately, analog cancellation only directly extends the receiver dynamic range by the difference in the received target output power and the receiver reference level (related to the internal local oscillator power of the mixer in the receiver). The theoretical maximum intermodulation dynamic range for a system would occur for no measurement path loss and no excess noise above the receiver sensitivity. This is impractical, since power combiners in the measurement path have inherent loss and extra measurement path loss is often needed to ensure the target output power is below the maximum output power of the vector modulator, particularly for low-loss targets. Target loss (either insertion loss or reflection loss depending on the measurement configuration) is beneficial to intermodulation dynamic range by relaxing the minimum cancellation requirement. Not explicitly shown, target loss also suppresses noise generated on the probing path prior to interaction with the target, potentially improving the minimum detectable signal level as well.

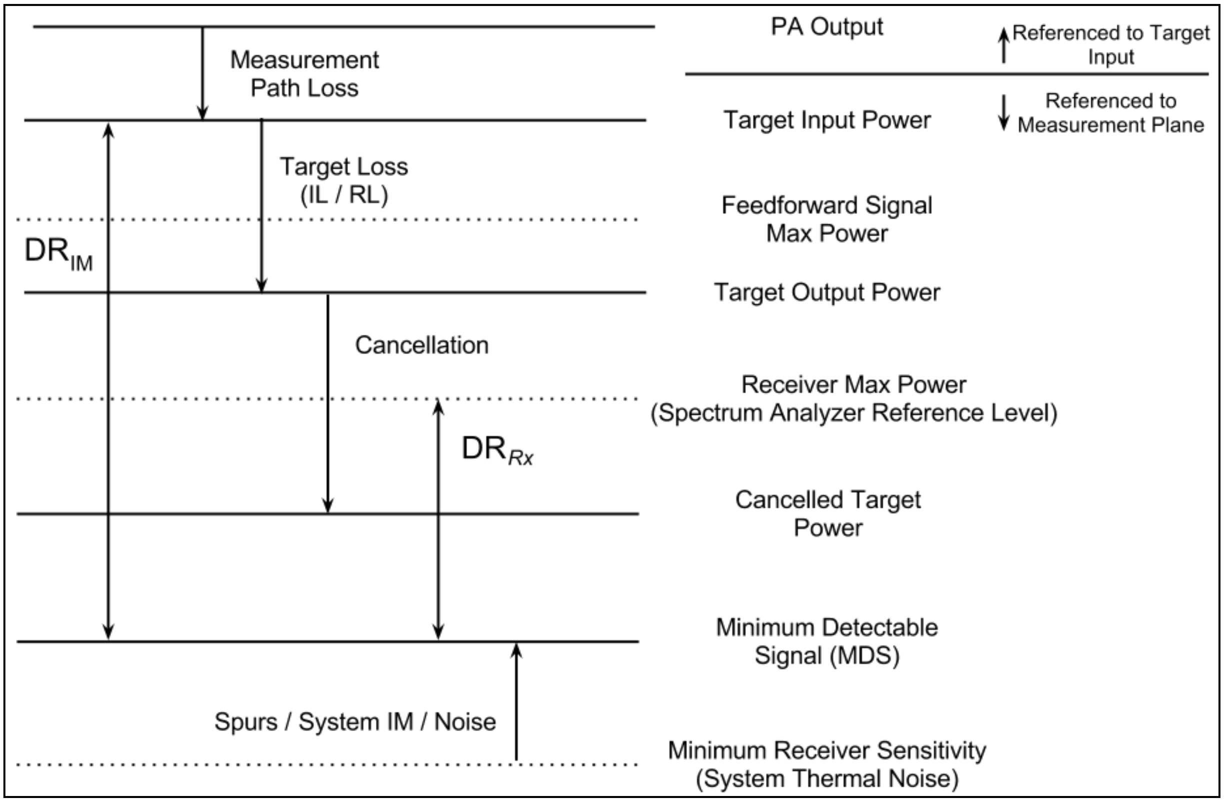

Figure 7. Relationships between power levels and dynamic range in the measurement system.

Figures 8 and 9 show the measured intermodulation dynamic range of the system in both transmission and reflection test configurations for several reference cases. The "Short" reflection measurement represents the worst-case DR_{IM} for system-generated intermodulation products, due to the maximum amount of power reflected back into the high-power amplifiers. The short should not generate any intermodulation, since it is a nearly ideal component. The "Cable" measurements are for a roughly 100-m-long, low-PIM cable and represents roughly the best-case DR_{IM} for a practical measurement. It has been shown that this cable produces no measurable PIM in this system. The "TEM" measurements are for a medium-sized transverse electromagnetic (TEM) cell, used for wireless probing of targets. Due to very poor matching of the TEM cell to 50 ohms, the dynamic range with the cell appears similar to the short, with the exception of several self-generated intermodulation spurs at resonant frequencies of the cell.

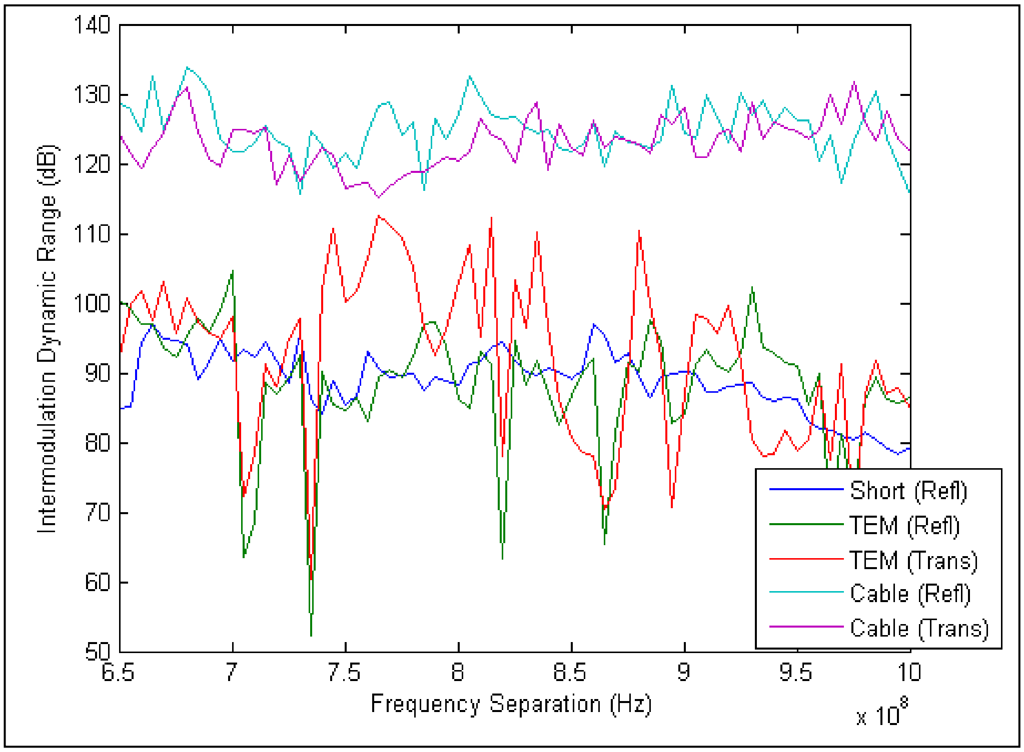

Figure 8. Measured intermodulation dynamic range over frequency.

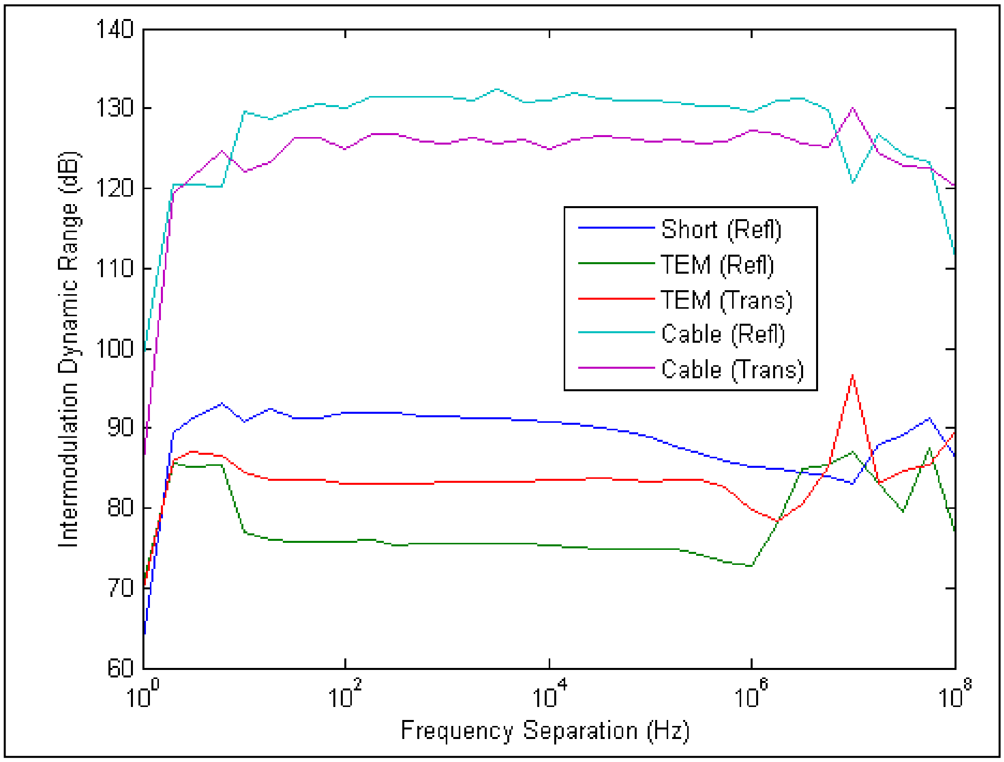

Figure 9. Measured intermodulation dynamic range over frequency separation.

5. Conclusions

A nonlinear measurement system has been implemented using an analog canceller to improve characterization of weakly nonlinear systems. While the target or device under test may often exhibit highly nonlinear behavior in wired (conducted) situations, the coupling of electromagnetic energy into the target from a remote source is usually very low and any distortion or intermodulation products generated are lower still. The implemented system uses high gain power amplifiers to drive a moderately high-power two-tone probing signal. The high-power signal is expected to generate low-level intermodulation distortion measurable in the return signal after interaction with the target. To extend the dynamic range of the receiver for very low-level nonlinear detection in the presence of the high-power stimulus signal, feedforward analog cancellation is used to remove the large interfering tones. The analog canceller is automated using digitally controlled vector modulators with an efficient cancellation algorithm and allows for measurement of nonlinear distortion very close in frequency to the cancelled stimulus tones, normally suppressed in filter-based systems, over a large bandwidth.

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List of Symbols, Abbreviations, and Acronyms

ARL	U.S. Army Research Laboratory
DAC	digital-to-analog converter
MDS	minimum detectable signal
PIM	passive intermodulation
RF	radio frequency
TEM	transverse electromagnetic

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US ARMY RESEARCH LAB
RDRL CIO LL
2800 POWDER MILL RD
ADELPHI MD 20783-1197

1 DIRECTOR
US ARMY RESEARCH LAB
RDRL CIO LT
2800 POWDER MILL RD
ADELPHI MD 20783-1197

5 DIRECTOR
US ARMY RESEARCH LAB
ATTN RDRL-SER-U
MATTHEW HIGGINS
ANTHONY MARTONE
DAVID MCNAMARA
GREGORY MAZZARO
ANDERS SULLIVAN
2800 POWDER MILL RD
ADELPHI MD 20783-1197

1 NORTH CAROLINA STATE UNIVERSITY
ATTN JOSHUA WETHERINGTON
2410 CAMPUS SHORE DRIVE
RALEIGH, NC 27606

TOTAL: 10 (1 ELEC, 9 HCS)

INTENTIONALLY LEFT BLANK.