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Apodization of Spurs in Radar Receivers Using Multi-Channel Processing

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Abstract

Spurious energy in received radar data is a consequence of nonideal component and circuit behavior. This might be due to I/Q imbalance, nonlinear component behavior, additive interference (e.g. cross-talk, etc.), or other sources. The manifestation of the spurious energy in a range-Doppler map or image can be influenced by appropriate pulse-to-pulse phase modulation. Comparing multiple images having been processed with the same data but different signal paths and modulations allows identifying undesired spurs and then cropping or apodizing them.

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Contents

Foreword

This report details the results of an academic study. It does not presently exemplify any modes, methodologies, or techniques employed by any operational system known to the author.

Classification

The specific mathematics and algorithms presented herein do not bear any release restrictions or distribution limitations.

This distribution limitations of this report are in accordance with the classification guidance detailed in the memorandum "Classification Guidance Recommendations for Sandia Radar Testbed Research and Development", DRAFT memorandum from Brett Remund (Deputy Director, RF Remote Sensing Systems, Electronic Systems Center) to Randy Bell (US Department of Energy, NA-22), February 23, 2004. Sandia has adopted this guidance where otherwise none has been given.

This report formalizes preexisting informal notes and other documentation on the subject matter herein.

1 Introduction & Background

As a practical matter, real radar systems are composed of real components that always exhibit some degree of nonideal behavior. Such components often exhibit non-linear behavior and/or other imbalances. In range-Doppler radar data, this manifests often as spurious signals, often just called "spurs", that falsely indicate target energy thereby reducing the performance, accuracy, reliability, and/or general utility of the radar system.

Radar systems that utilize range-Doppler data and are subject to such performance degradation include, but are not limited to

1. Synthetic Aperture Radar (SAR),
2. Inverse-SAR (ISAR),
3. various Moving Target Indicator (MTI) radar modes and systems, and
4. various Wide Area Search (WAS) radar modes and systems.

In addition, imbalance in the channels of a quadrature demodulator will exhibit ghosting that may also be characterized as spurious energy. Such quadrature demodulators may be employed more broadly than just for generating range-Doppler radar data.

The typical spur mitigation strategy is to pay very close attention to component selection, circuit construction, circuit layout, and circuit fabrication to minimize the susceptibility to spur creation. Thereafter, heuristic techniques are sometimes employed to desensitize the radar to offending spurs. Spurs that survive these measures may still be of sufficient energy to render false alarms.

In recent years, several signal processing techniques have been developed to treat spurs in manners to reduce their impact on the desired radar operation.

<u>Move Spur to Unused Doppler</u>

One class of techniques seeks to move the spurious energy to unused or unimportant parts of the range-Doppler map.

> Doerry and Tise[1] show how I/Q imbalance spurious energy can be moved to Doppler regions not useful for SAR imaging. This is also detailed in a later report by Doerry.[2]

Such techniques, however, are not useful by themselves when the entire Doppler spectrum is of interest for target detection.

Smear Spur with Modulation

Another class of techniques seeks to smear the offending spurious energy in one or more dimensions, thereby reducing the peak value of the spur to something below the detection threshold.

> Dubbert and Tise[3] show how a residual chirp modulation can be used to smear spurious energy generated by an Analog-to-Digital Converter (ADC).
>
> Brannon shows how spurious energy due to ADC non-linearity can be mitigated with a dither signal.[4]

Such techniques do not eliminate the spurious energy, merely redistribute it in the hope of reducing their impact on false alarm detections.

Both techniques employ appropriate modulation/demodulation before/after the spurious energy generation point.

Cancel Spur with Predistortion

Sometimes, some spurs can be measured and cancelled by suitable waveform manipulation.

> Dubbert and Dudley[5] show how a noise dither can effectively cancel a DC leakage in a quadrature mixer.

This can only happen if the spur is stable and predictable, which is problematic for most spurs.

Apodization

With malice of forethought, we observe that sometimes undesired energy can be effectively cropped, or apodized, when there is the ability to identify it as such. This requires a reference signal of some sort. We note that such a reference signal need not necessarily be perfect, just sufficient to discriminate the offending energy.

> An apodization techniques for interference suppression in a SAR image was detailed in a report and patent by Doerry.[6,7] Essentially, the same digital data was processed twice, with different processing parameters, and a minimum was chosen from the corresponding results.

In this report we will show how a suitable reference can be generated to apodize spurs in a range-Doppler map.

2 Overview & Summary

We propose herein to split the received radar echo signal into two channels. The split will occur prior to the entry point for the spurious energy. Each channel will be processed independently, and somewhat differently, but in a manner to eventually create the same range-Doppler map for any desired signals.

The difference in processing will include analog modulation to move the spurious energy in the range-Doppler map with respect to the desired signals. Each channel will employ modulation to move the spurious energy in a manner different from the other. The difference may include modulating only one channel and not the other. The unique analog modulation will be removed by digital signal processing in the digital data.

The resulting two range-Doppler maps, one from each channel, will then exhibit identical true signals, but differing spurious energy content.

Finally, a composite range-Doppler map will be created by combining the two individual maps in a manner to reject the spurs. This rejection algorithm might be to select a pixel value that is the minimum of the magnitudes of the corresponding pixels from the two independent channels.

We exemplify this in Figure 1. Although we illustrate the spurious energy being added to the signal paths, we stipulate that its initial generation may also be a function of the data itself due to nonideal components in the analog signal path.

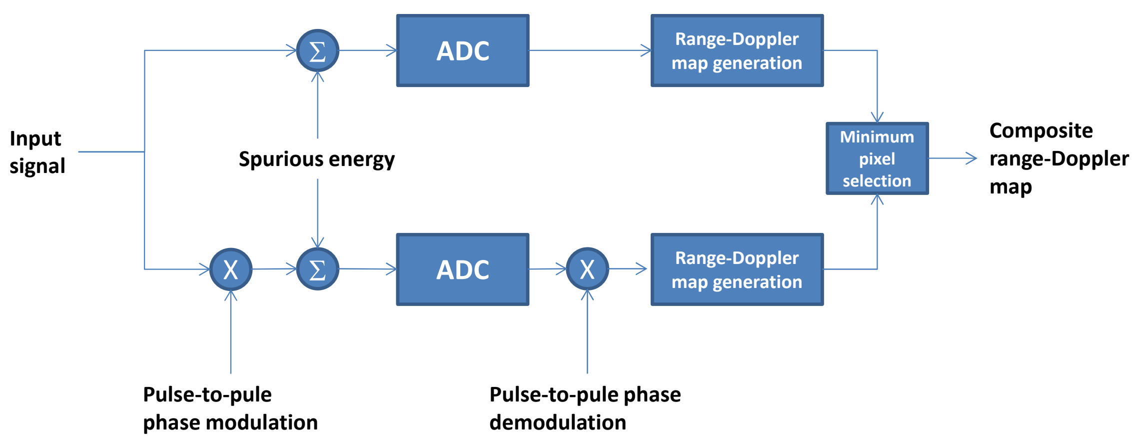

Figure 1. Example spur mitigation signal processing algorithm.

"When the meaning is unclear there is no meaning."
— *Marty Rubin*

3 Detailed Analysis

3.1 Sources of Spurious Signals

Spurious energy may be introduced into a signal path in any of a variety of manners. We briefly examine some of the more common mechanisms here.

3.1.1 I/Q Imbalance

Radar signal processing often employs quadrature demodulation, where radar echoes are demodulated to baseband in a manner to generate complex data (e.g. with each data sample exhibiting real and imaginary numerical components, otherwise known as in-phase 'I' and quadrature 'Q' components, respectively). Sometimes creation of I/Q components is done with analog signals and processing, and sometimes creation of I/Q components is done with digital data.

With analog quadrature demodulation, the signal is split into separate analog channels, thereby allowing for analog component differences to manifest an imbalance between I and Q data characteristics.

With digital quadrature demodulation the signal is sampled at an intermediate frequency with final down-conversion to I and Q components using Digital Signal Processing (DSP). However the nature of the processing is often such that nonideal behavior of the Analog-to-Digital Converter (ADC) still manifests an imbalance between I and Q data characteristics.

In either case it is quite common for the resulting data to manifest an imbalance between I and Q components. This results in 'ghost' target echoes that mirror the true target echoes with a symmetry characterized as a 180 degree rotation about the 2-dimensional zero-frequency point in the image, called the "DC-point" of the image. This is illustrated in Figure 2, and described in a report by Doerry.[8]

This DC-point about which the ghost is rotated is the DC-point of the raw data at the ADC, and corresponds to the zero-Doppler frequency at the ADC, and not necessarily after any pulse-to-pulse phase demodulations or corrections to the digital data prior to generating the image. Consequently, by moving the raw data's DC point, we also move the ghost target. This is illustrated in Figure 3. Note that the true target remains in the proper location, but the ghost target has shifted.

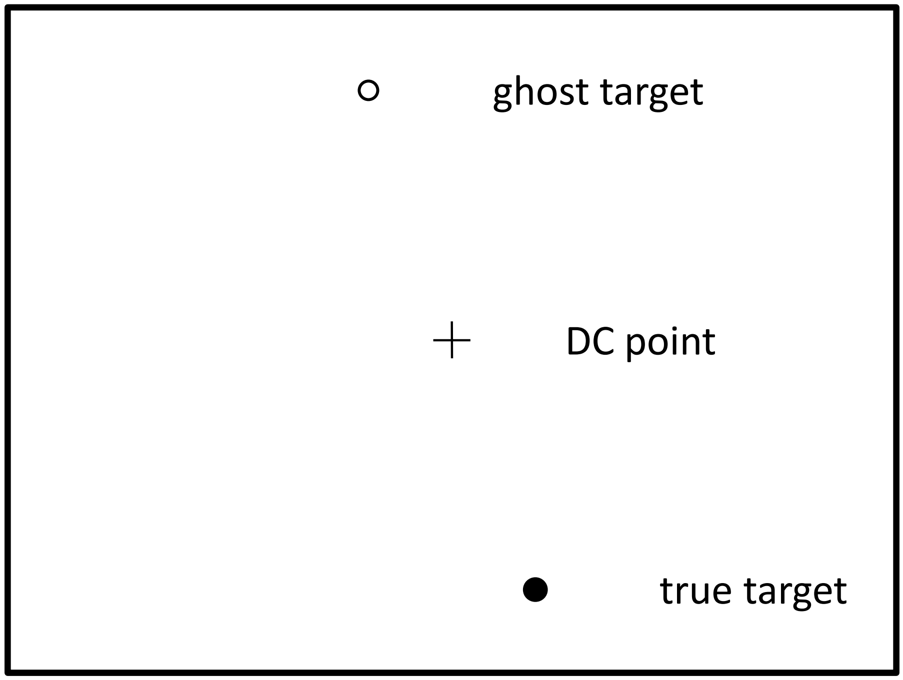

Figure 2. Example of I/Q imbalance manifestation.

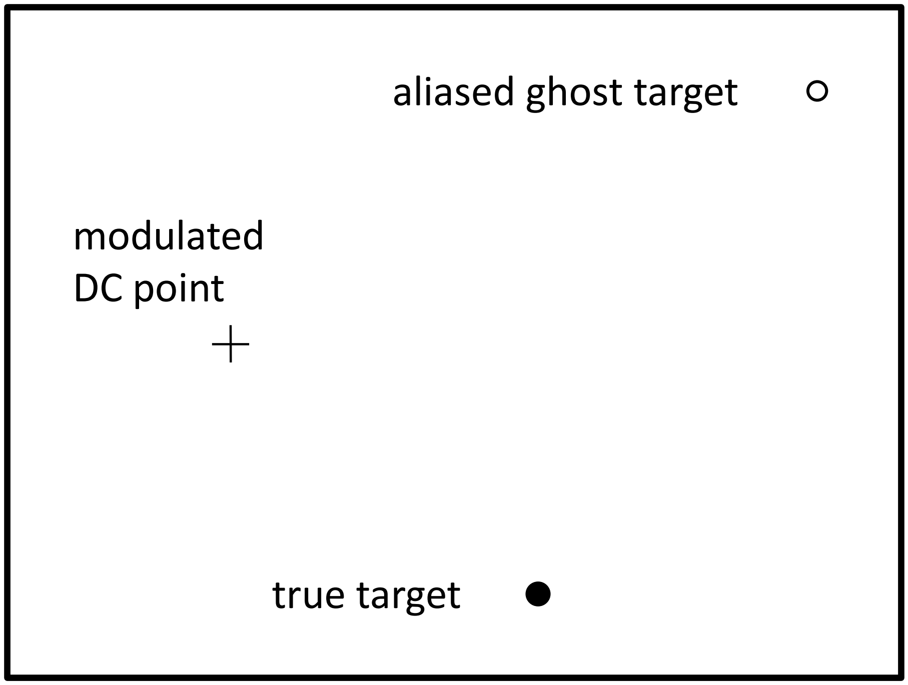

Figure 3. Example of I/Q imbalance manifestation with shifted raw-data DC point.

3.1.2 ADC Nonlinearities

The ADC is a complicated component. Its purpose is to render an analog voltage at its input into digital words that represents quantized versions of a specific time samples of the input voltage. The typical ADC is designed to quantize input voltages with linear increments of amplitude. However, in spite of the design intent, some degree of non-linearity is inevitable. That is, there is an inherent non-linearity in the ADC conversion process; undesirable, typically small, but definitely there.

The unknown and undesired nonlinearity aspects of an ADC are embodied in the ADC's Differential Nonlinearity (DNL) and its Integral Nonlinearity (INL) specifications.

A good primer on INL is an Application Note by Maxim Integrated Products, Inc.[9]

Measurement of INL and DNL is addressed in an Application Note from Analog Devices.[10]

Kester discusses other ADC component specifications that also manifest nonideal behavior similar to nonlinearity.[11]

As with all non-linear functions, the effect to the signal is to generate harmonics and other mixing products that corrupt the data. This happens right inside of the ADC, and is unaffected by any filters that precede the ADC. Furthermore, these spurious harmonics and mixing products will alias unimpeded by any filters.

The bottom line is that harmonic spurs may be shifted in range as well as Doppler. Consequently, spurious energy can manifest anywhere in the range-Doppler map. Furthermore, different harmonic spurs may exhibit any combination of same or different range or Doppler. The effect of ADC nonlinearity is illustrated in Figure 4.

Note that the instantaneous ADC sample magnitude is altered with a phase shift. Consequently, we may expect the location and intensity of any given harmonic spur to be altered by applying a phase modulation prior to the ADC, as if by shifting the raw data's DC point, and of course removing it in the data thereafter. This is illustrated in Figure 5. Note that the true target remains in the proper location, but the harmonic spurs have shifted.

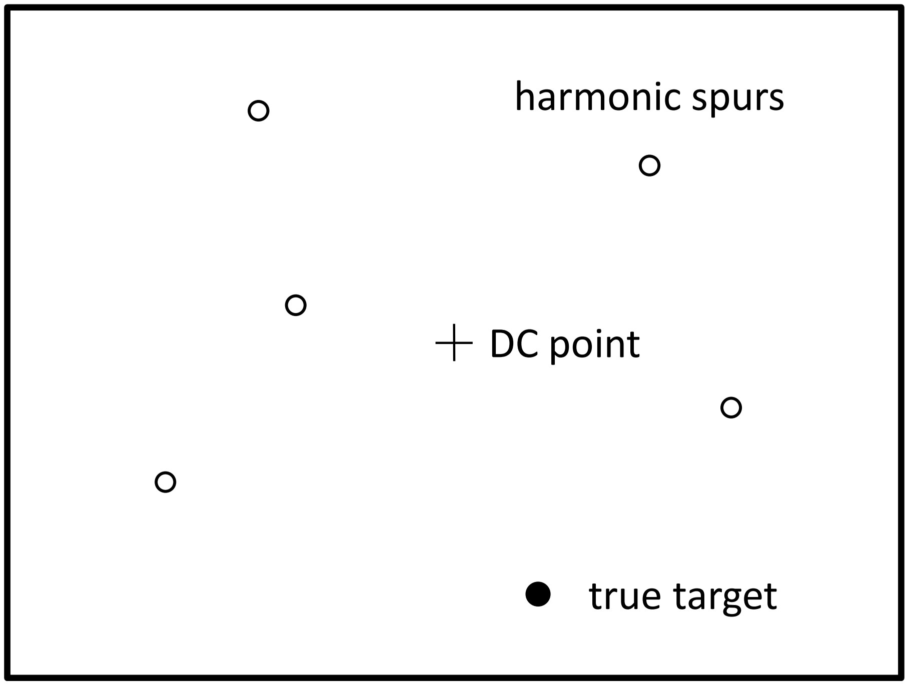

Figure 4. Harmonic spurs generated by ADC INL.

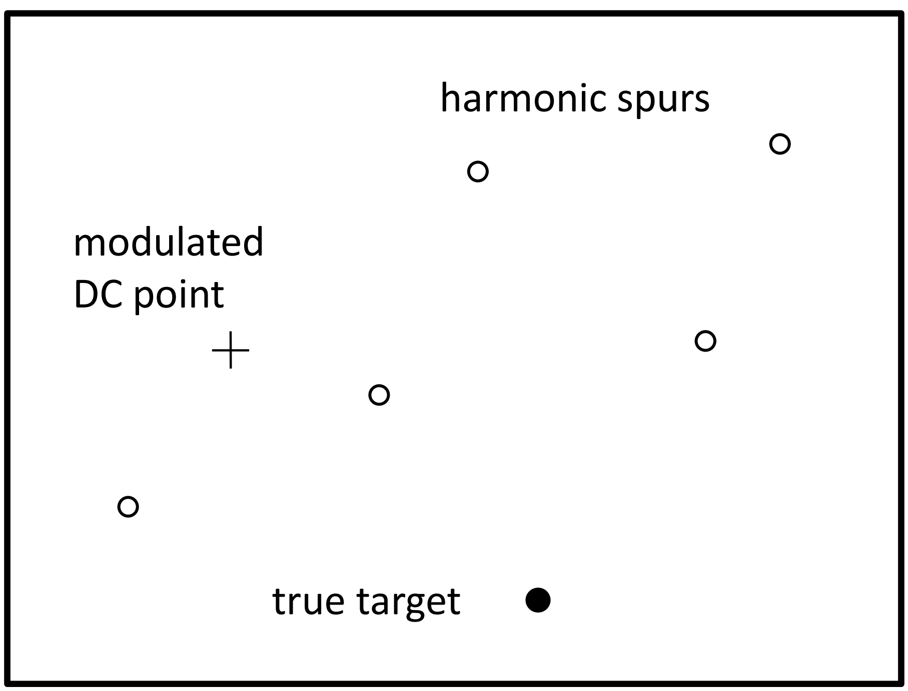

Figure 5. Harmonic spurs generated by ADC INL with shifted raw-data DC point.

3.1.3 Additive Interference

Both I/Q imbalance and ADC nonlinearity can generate spurious energy, but require a legitimate true target signal to be present to do so.

However, other spurious energy can manifest in range-Doppler images even without the presence of a true target signal. These are termed additive spurious energy, also known as additive interference. Such additive spurious energy is often the result of undesired coupling of legitimate signals, but via undesired coupling paths. This is not uncommon in high-speed mixed-signal printed wiring boards, even in spite of careful circuit design, and is particularly problematic for large dynamic-range systems like coherent radar systems.

Dudley[12] discusses the difficulties designing high-performance mixed-signal circuit boards

However, for these signals to manifest as strong signals in the range-Doppler image, they must be reasonably coherent with the radar's Pulse Repetition Frequency (PRF). Consequently, they may be shifted in Doppler by applying and then removing an appropriate Doppler offset, in a manner similar to shifting spurs due to I/Q imbalance and ADC nonlinearity. This is illustrated in Figure 6 and Figure 7.

Note that the additive interference spurs have shifted between the two range-Doppler images.

3.1.4 Summary

In all cases, the location of spurious energy in the range-Doppler map will be a function of any modulation applied before the spur's entry, and subsequent demodulation in the data. True target energy remains fixed, but spurious energy is shifted.

We will exploit this in the subsequently described mitigation scheme.

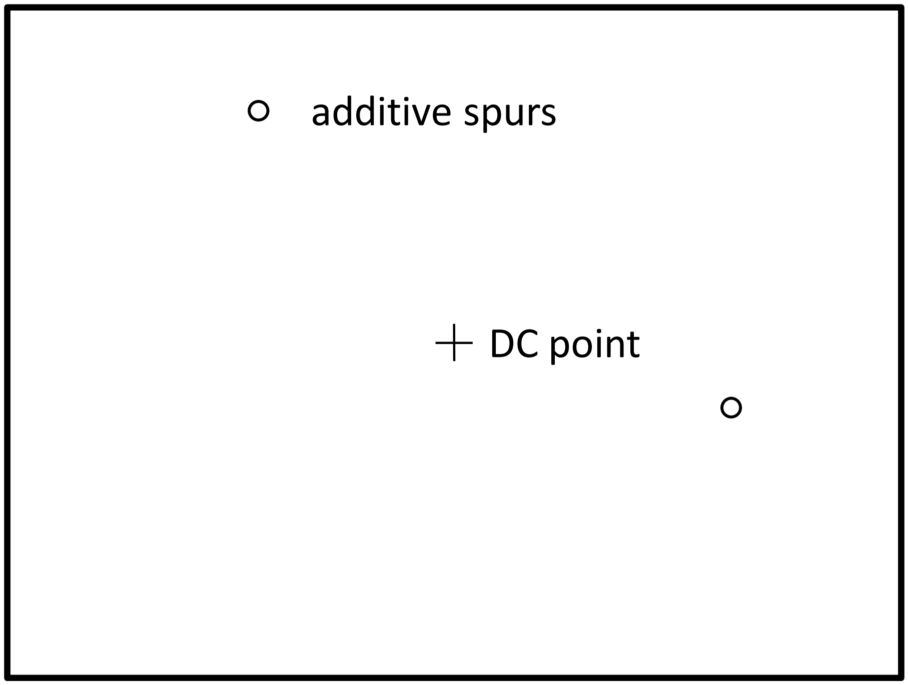

Figure 6. Additive spurs.

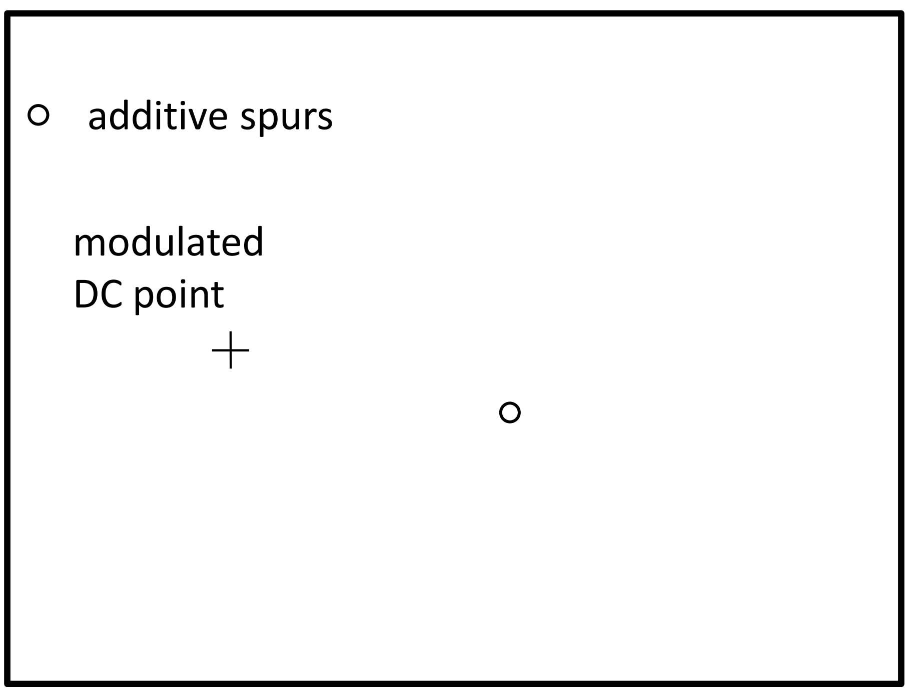

Figure 7. Additive spurs with shifted raw-data DC point.

3.2 Mitigation Procedure

From the preceding analysis, we readily observe that by processing the same signal both with and without appropriate pulse-to-pulse phase modulation, we may affect the location of spurious energy and discriminate it from true target energy. Herein we propose to do exactly that.

With respect to Figure 1, we observe that we can apply the input signal to two separate and independent signal paths. For convenience we identify them as Signal Path #1, and Signal Path #2.

In Signal Path #1 we may process the signal in a conventional manner, yielding a conventional range-Doppler image, albeit with spurious energy manifested due to any of the aforementioned sources.

In Signal Path #2 we will first apply a pulse-to-pulse phase modulation. One such phase modulation might be a rolling phase shift that increments by $\pi/2$ radians per pulse. This phase shift must be applied prior to the entry point, or creation point of the spurious energy. The signal is then processed in a similar manner as the other signal path, and digitized accordingly. After the ADC renders the signal into data, and beyond the point where any new spurious energy enters the signal path, the aforementioned pulse-to-pulse phase modulation is removed, or compensated, yielding a range-Doppler image similar to that of Signal Path #1, insofar as the location of true target data. However, the image of Signal Path #2 will have spurious energy located in different locations as compared to the image of Signal Path #1.

At this point we have two range-Doppler images, each with true targets identically located, but with spurious energy displaced from each other. We illustrate these two maps superimposed onto each other in Figure 8.

We may now combine the two range-Doppler images into a single range-Doppler image by selecting from the pair of images for each pixel the corresponding pixel with minimum magnitude. We illustrate this in Figure 9. The resulting composite range-Doppler image may then be processed in the conventional manner for the radar mode employed.

Alternatively, for some modes where the range-Doppler image is further processed for target detections, such as for MTI modes or WAS modes, we may forego the combining of the two range-Doppler images and perform target detection operations on the two images independently. A voting scheme may then be employed in that only detections common to both range-Doppler maps will be reported, and those not present in both will be culled from the set of target detections.

Another possibility might be to examine the complex covariance (coherence) between the two images as an indicator of the location of the spurious energy. This might then be used as a mask to pass only legitimate true targets.

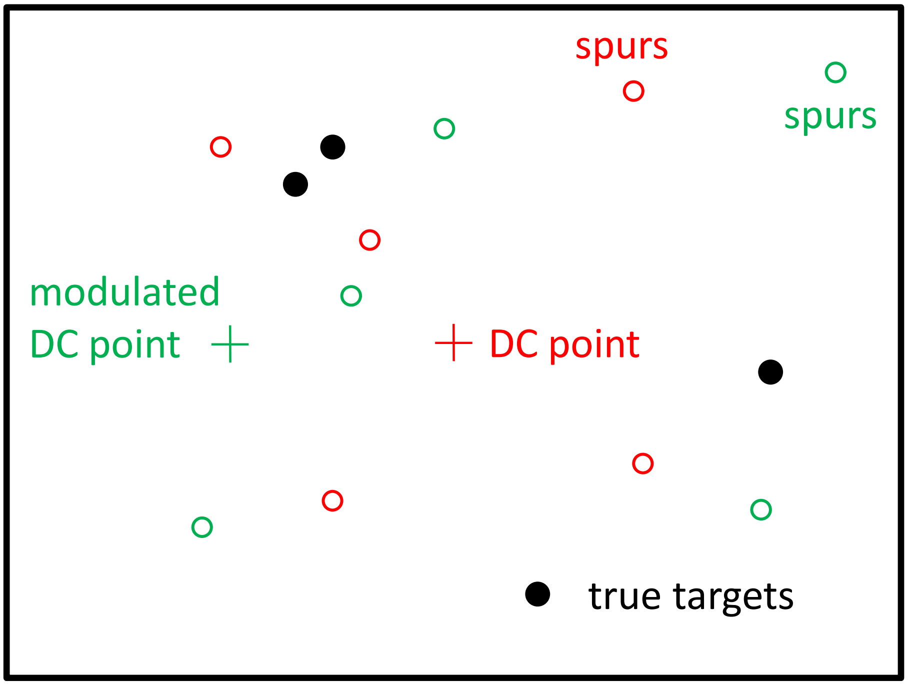

Figure 8. Superimposed range-Doppler images with spurious energy displaced from each other. Red spurs are evident in Signal Path #1, and green spurs are evident in Signal Path #2.

Figure 9. Composite range-Doppler map where pixels are selected from corresponding map locations exhibiting minimum magnitude. Spurs have been apodized.

Nevertheless, in all cases the spurious energy is effectively cropped or “apodized” from the radar output data.

Although we have shown a case where Signal Path #1 receives no pulse-to-pulse modulation, and Signal Path #2 does receive pulse-to-pulse modulation, this was merely a convenience to illustrate the point that different modulation schemes on the two signal paths will yield different spurious energy locations with respect to the true target locations. Modulation schemes might be applied to either or both of the signal paths. The only requirement is that they result in spurious energy being displaced differently from each other with respect to the true target locations.

"When there is no distraction, there is clarity."
— Lorii Myers, No Excuses, The Fit Mind-Fit Body Strategy Book.

4 Conclusions

The following points are worth repeating.

- Spurious energy is often evident in a range-Doppler image or map, and is due to nonideal component or circuit behavior. This might be due to I/Q imbalance, nonlinear component behavior, additive interference (e.g. cross-talk, etc.), or other sources.

- The location of the spurious energy in the range-Doppler image may be influenced by suitable modulating the data before the spur entry point, and correspondingly demodulating the data after the spur entry point. The modulation is advantageously a pulse-to-pulse phase modulation.

- By applying the received signal to two signal paths, each with different modulations, two range-Doppler images may be generated, each with identical true target responses, but each with different spurious energy responses.

- The two resulting range-Doppler images may be combined by selecting on a pixel by pixel basis the pixel with the smallest magnitude.

- Alternatively, for some radar modes, both range-Doppler images may be processed for target detections, with a voting scheme to distinguish real target detections from inadvertent spurious false target detections. Only targets evident identically in the same location in both images are real targets.

“Never worry about theory as long as the machinery does what it's supposed to do.”
-- Robert A. Heinlein

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