

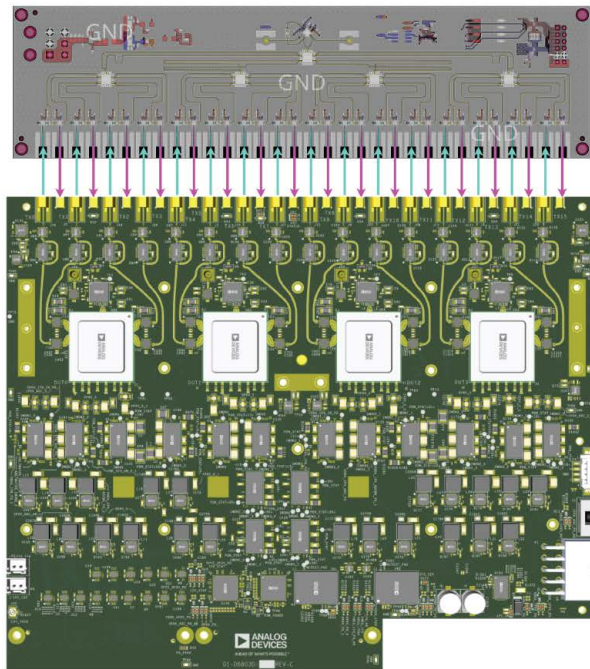
Calibration Implementation Techniques for Multichannel Phased-Array Subsystems

This article describes and comparatively evaluates two approaches to phase calibration of a 16-channel (transmit and receive) X-band phased-array subsystem.

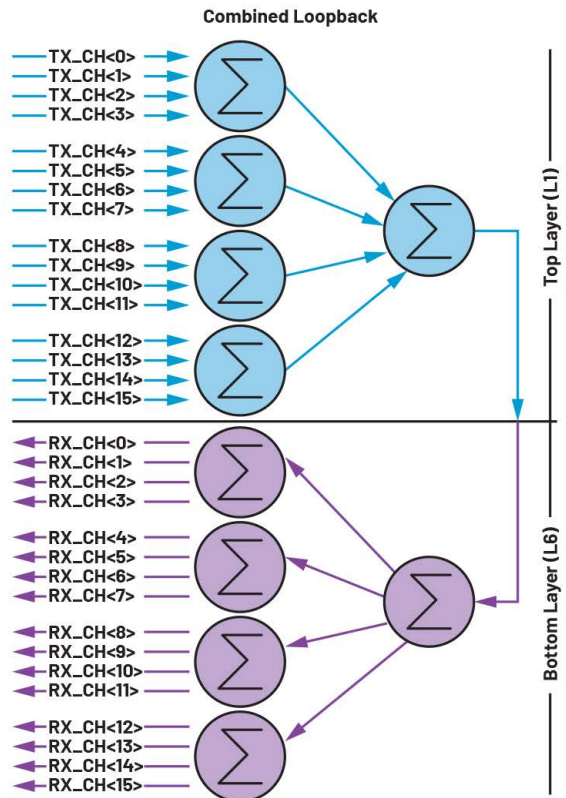
Accurate amplitude and phase calibration is essential to achieving the theoretical performance of phased-array antenna systems. Proper calibration applies the correct phase and amplitude weighting to each antenna element. This ensures that desired

signals combine constructively (coherently) while noise, being uncorrelated between elements, combines less efficiently (noncoherently).

The result is improved signal-to-noise ratio (SNR) and consistent antenna pattern performance across varying fre-



(a)



Simplified Diagram

(b)

1. Shown at left is the ADXBAND16EBZ and ADXBAND16EBZ-CAL connection (a) and at right is the combined loop-back block diagram (b). (Credit: Analog Devices)

quencies, temperatures, and operating conditions.

This article focuses specifically on two phasealignment techniques used for the evaluation and characterization of the [ADX BAND16EBZ](#) X-band phased-array reference design.¹ The analysis uses continuous-wave (CW) waveforms and leverages the hardened digital-signal-processing (DSP) blocks of Analog Devices' [AD9084](#) Apollo mixed-signal front-end device.

The system also utilizes prerequisite multichip synchronization to ensure phase determinism. However, the details of this synchronization process are outside the scope of this article.

Two Phased-Array Calibration Techniques Explained

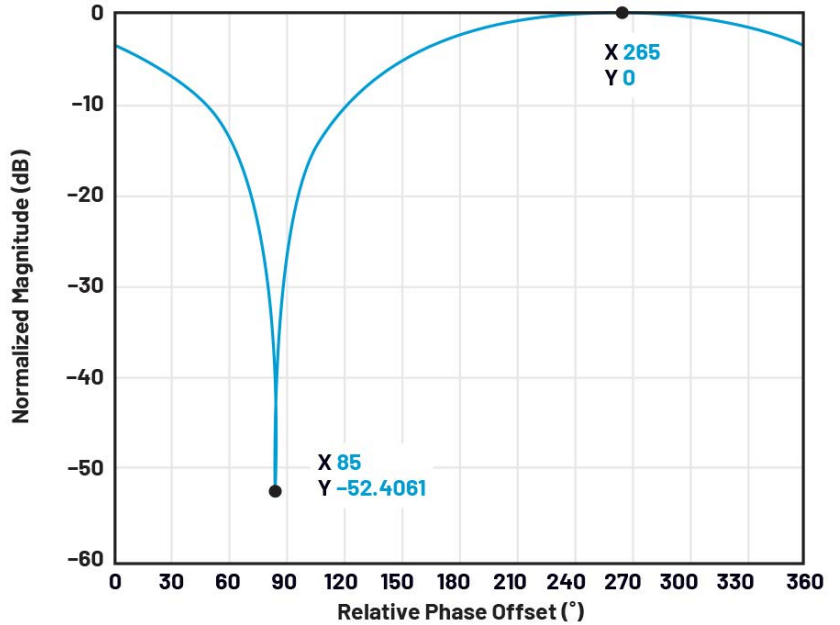
Calibration on the subsystem platform is essential for ensuring that all 16 transmit and receive channels operate coherently. When the channels align in time, phase, and amplitude, the system achieves the expected coherent combining gain of approximately 24 dB ($20 \times \log_{10}(16)$).

Here, we consider two distinct calibration approaches: the null-power method and the crosscorrelation method. The first is a traditional approach that excels in robustness, while the second is a modern, quicker alternative leveraged as the primary method for characterization.

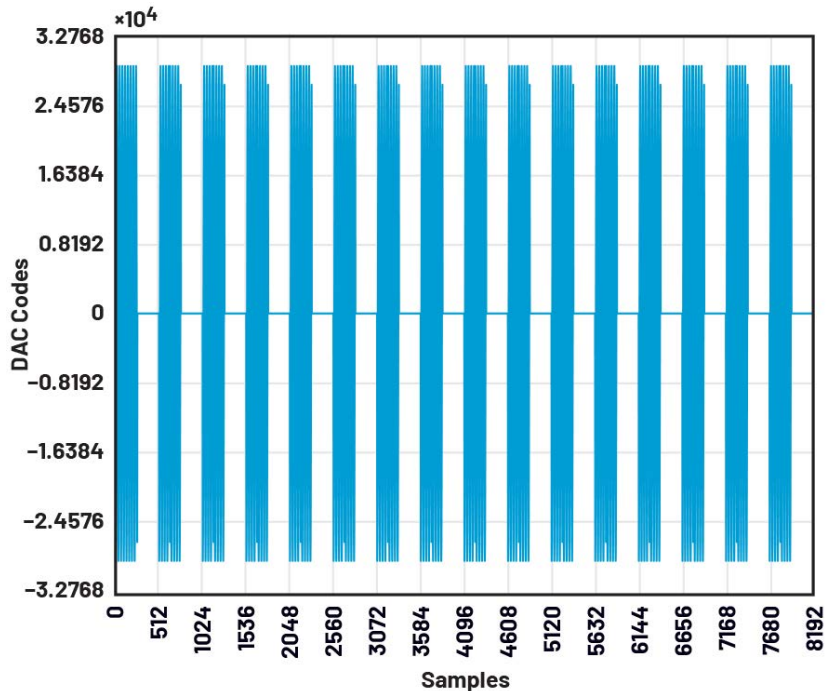
In both cases, we leverage a passive calibration board consisting of a power combiner/splitter and switch network to enable a self-contained transmit-to-receive loopback (Fig. 1). The following sections describe both methods in a detailed, engineering-accurate manner and explain how the system extracts the final transmit and receive phase offsets.

The Null-Power Phased-Array Calibration Method

The null-power method is based on rotating the phase of one channel relative to a reference with fixed phase and observing the superposition magnitude of the two combined channels. The peak magnitude is recorded for each phase step and 180° is added to the phase offset corresponding to the two-channel combined minimum (null) (Fig. 2).



2. This plot depicts the magnitude response for the null-power method comparing phase contributions of two combined channels. (Credit: Analog Devices)



3. All DAC waveforms are combined to create a time-interleaved pulsed waveform. Each pulse train corresponds to an independent transmit channel. (Credit: Analog Devices)

The phase offset is then applied to the numerically controlled oscillator's (NCO's) phase shifter of the corresponding channel so that the channel aligns constructively with respect to the selected reference channel. The entire procedure must be repeated for each channel and for each frequency of interest.

Although this approach requires significant time due to

its swept nature, it's extremely robust in noisy or unpredictable environments. It leverages a sinusoidal waveform and doesn't rely on timing alignment or correlation-based measurements. The main drawbacks are the execution time and the limited information it provides because it yields only phase-offset information.

Additional optimization can be implemented for quicker sweeps using this method. Instead of a fixed phase step, one could start with a coarse step size to find a general range for the null location and use a finer phase-step size to dial in the exact offset for the corresponding null.

The Cross-Correlation Phased-Array Calibration Method

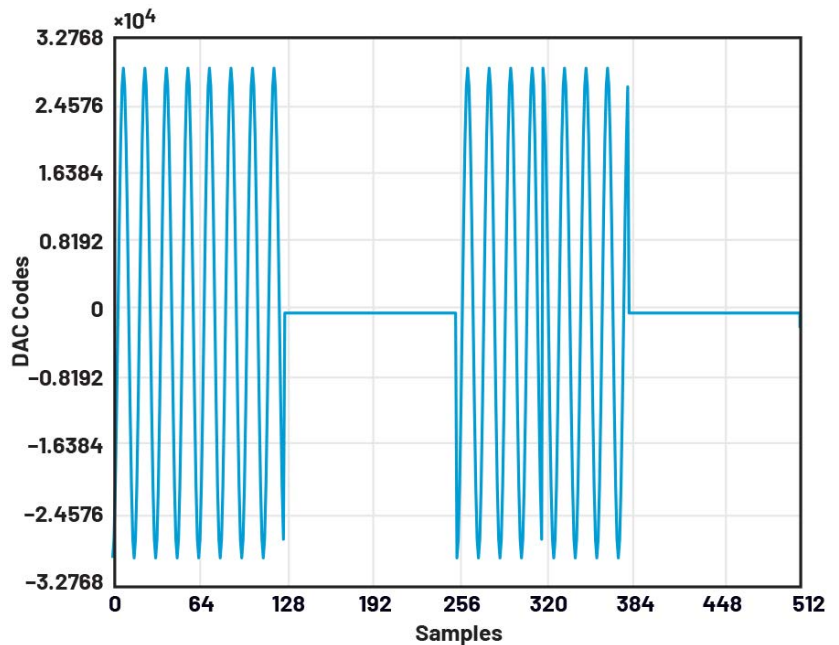
The cross-correlation method is the standard calibration procedure because it aligns phase rapidly and with high precision. The method begins by configuring the calibration board into combined-loopback mode. All transmit and receive NCO phases, including both main and per-channel adjustments, are set to zero so that any measured phase error originates solely from the hardware signal chain.

Next, we generate a pulsed baseband waveform with one pulse assigned to each digital-to-analog converter (DAC) channel in a time-division fashion akin to time-division multiple access (TDMA). These pulses are placed in discrete time slots in a time-interleaved fashion to produce a frame containing 16 non-overlapping pulses once all channels are combined (Fig. 3). We transmit this waveform at the operating RF frequency to serve as the reference for the correlation-based alignment.

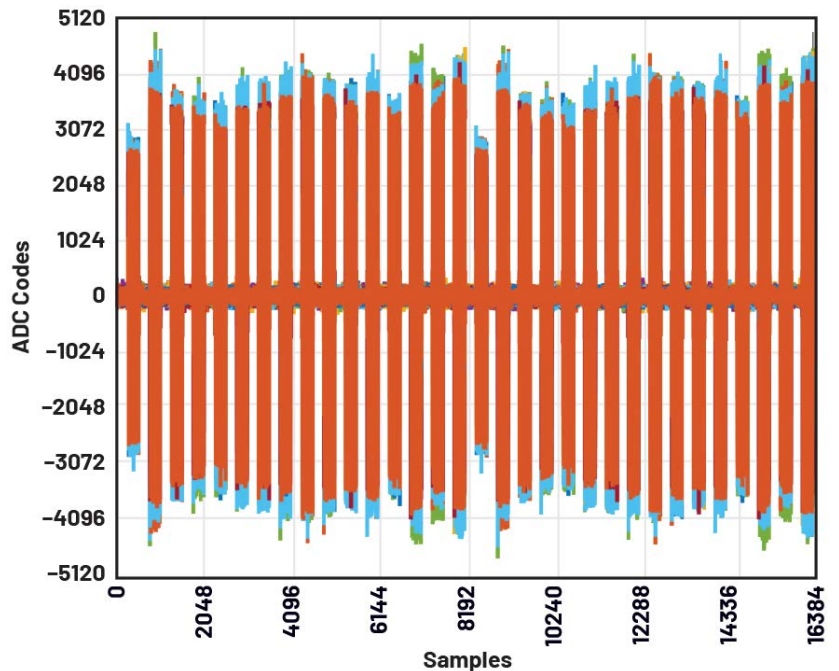
The pulse corresponding to TX_CH<0> has a seven-sequence [Barker code](#), where each sinusoidal period within the pulse envelope of TX_CH<0> has a unique sequence of phase shifts. This helps distinguish the reference channel compared to the other channels by a higher SNR signature in the correlation response. Channels 1 to 15 all have a five-sequence Barker code with its own unique phase-shift sequence. A comparison of TX_CH<0>

and TX_CH<1> is shown in Figure 4.

The calibration process starts with each DAC transmitting its respective time-interleaved pulsed waveform and all analog-to-digital converters (ADCs) capturing the 10 data frames of the combined waveform. Each data capture for all 16 ADCs is taken at an arbitrary time, resulting in each data frame shifted by an unknown sample count relative to the



4. Shown here are TX_CH<0> (Pulse0) with a seven-sequence Barker code and TX_CH<1> (Pulse1) with a five-sequence Barker code. (Credit: Analog Devices)



5. Depicted are coherently summed ADC captures of the combined time-interleaved waveform synthesized by all DACs. It represents twice as many samples captured compared to transmitted. (Credit: Analog Devices)

others.

Sample misalignment correction is done by selecting an arbitrary data frame as a reference and executing an autocorrelation against all remaining data frames. Each capture is then sample shifted by the appropriate number of samples to achieve alignment based on the autocorrelation sample delay results. Once aligned, the data frames are coherently summed, thus improving the SNR for accurate post-processing (Fig. 5).

The next step cross-correlates the coherently summed data (Fig. 4, again) and the original transmitted time-interleaved pulse train waveform (Fig. 3, again). The resulting cross-correlation matrix aids in determining the phase offsets relative to a defined reference for all ADCs and DACs. The reference channels TX_CH<0> help identify its location in the time-interleaved pulses and can be used to determine the relative phase offsets of the remaining channels.

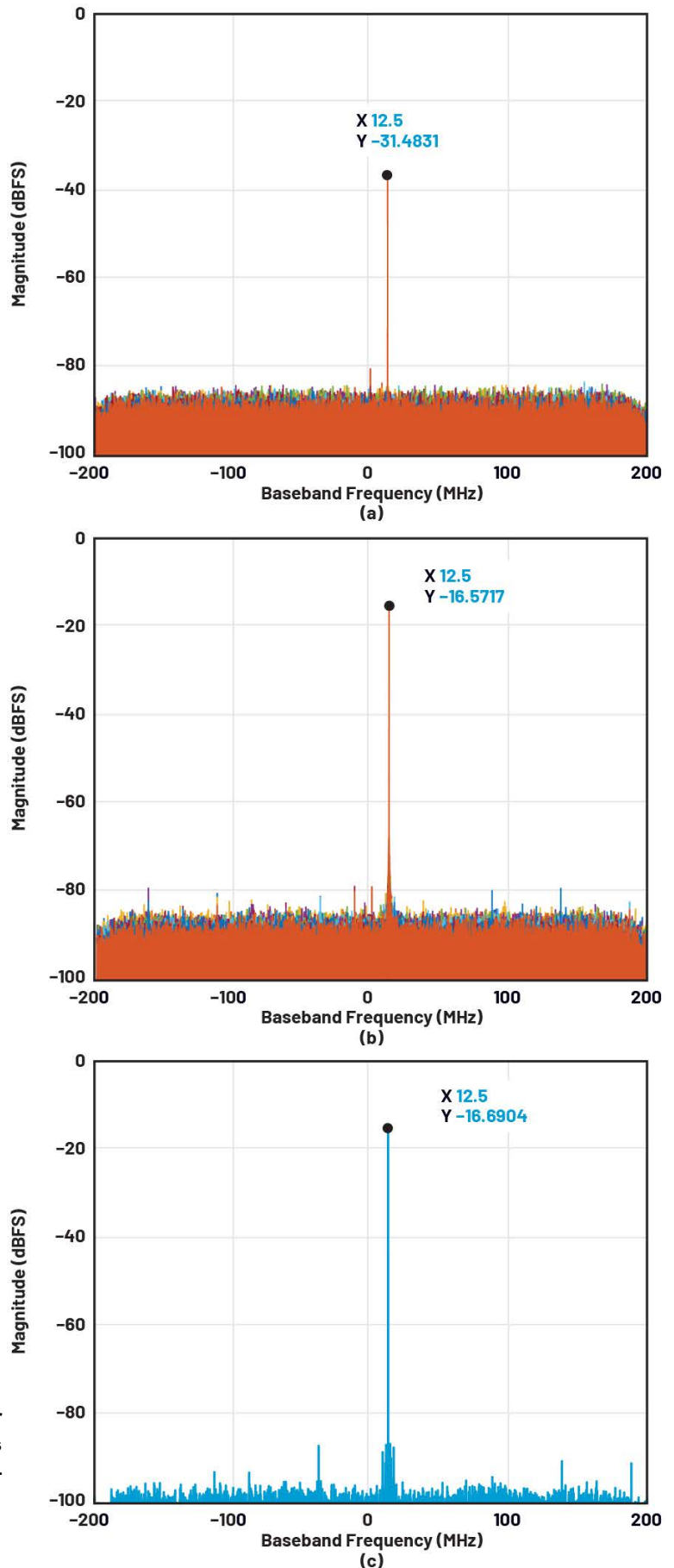
The relative difference of the complex angle of the peak correlation response for TX_CH<0> across the 16 ADC data frames determines the ADC NCO phase offsets. The relative difference of the complex angle of the peak correlations of TX_CH<15...1> compared to TX_CH<0> within a single ADC data frame determines the DAC NCO phase offsets. In both cases, the phase offsets are phase-wrapped into the range from -180° to $+180^\circ$ to be compliant with the AD9084 device drivers.

Validation of Final Calibration Results

With calibration completed and the derived phase offsets applied, the next step is to validate the effectiveness of the phase-alignment procedure. For a fully coherent 16-element array, the signal power is expected to increase by $20\log_{10}(16)$, while uncorrelated noise power increases by $10\log_{10}(16)$.

Figure 6a shows the magnitude of a single

6. Shown here are an FFT plot of a single transmit channel looped back into a single receiver (a), an FFT plot of 16 transmit channels combined and looped back into a single receiver (b), and an FFT plot of 16 combined transmit channels and 16 combined receive channels (c). (Credit: Analog Devices)



transmitted CW waveform digitized by one ADC channel, along with the fast Fourier transform (FFT) of the complex-valued data frame. *Figure 6b* depicts the combination of all 16 transmitted CW waveforms with the peak magnitude measured from the FFT of a single ADC frame. As expected, the coherent combination yields an approximately 23-dB increase in peak signal magnitude relative to *Figure 6a*.

Finally, *Figure 6c* presents the FFT obtained when all 16 transmit waveforms and all 16 receive channels are coherently summed. In this case, the peak magnitude reaches the average expected level due to bit-growth effects, while the uncorrelated noise combines noncoherently, resulting in an SNR improvement of about 12 dB.

In conclusion, we've demonstrated two practical calibration strategies for achieving coherent phase alignment in a 16-by-16 multichannel phased-array subsystem. The null-power method, while time intensive, offers a highly robust means of determining inter-channel phase offsets without reliance on precise timing or correlation metrics. Thus, it's well-suited for environments with elevated noise or measurement uncertainty.

In contrast, the cross-correlation method provides a rapid and highly accurate calibration approach by exploiting time-interleaved pulsed waveforms, Barker-coded channel identification, and coherent summation of multiple captures to improve SNR and estimation stability.

Measured results confirm that the correlation-based calibration achieves near-theoretical coherent combining performance, with signal power scaling as expected for a fully aligned 16-element array and noise combining noncoherently across receive channels. The ability to efficiently perform calibration across multiple frequencies enables the generation of high-resolution phase-correction tables suitable for temperature- and frequency-dependent system characterization.

While the current implementation focuses on narrow-band CW excitation, the methodology naturally extends to wideband calibration by leveraging the integrated finite-impulse-response filtering and DSP capabilities of the [AD9084](#). Future work will explore broadband excitation and frequency-dependent calibration to further enhance instantaneous bandwidth performance in large-scale digital beamforming systems.

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References

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2. Michael Jones, Travis Collins, and Charles Frick. "[Integrated Hardened DSP on DAC/ADC ICs Improves Wideband Multichannel Systems.](#)" Analog Devices, Inc., May 2021.