TI Designs

RF Sampling S-Band Radar Transmitter Reference Design

Description

A direct radio frequency (RF) sampling approach for a radar transmitter operating in S-band is demonstrated using the DAC38RF80 or DAC38RF83, dual-channel, 9-GSPS RF digital-to-analog converters (DACs). The RF sampling transmit architecture simplifies the signal chain, which brings the data converter closer to the antenna and allows flexibility with high-performance and high-signal bandwidths. This approach is demonstrated by building a transmitter to meet the requirements of multi-function phased array radar (MPAR) that can simultaneously be used for weather monitoring and air traffic control requirements.

Resources

TIDA-01240	Design Folder
DAC38RF80	Product Folder
DAC38RF83	Product Folder
ADC32RF45	Product Folder
LMK04828	Product Folder

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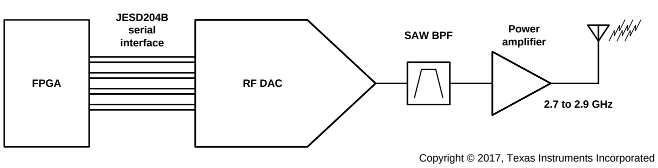
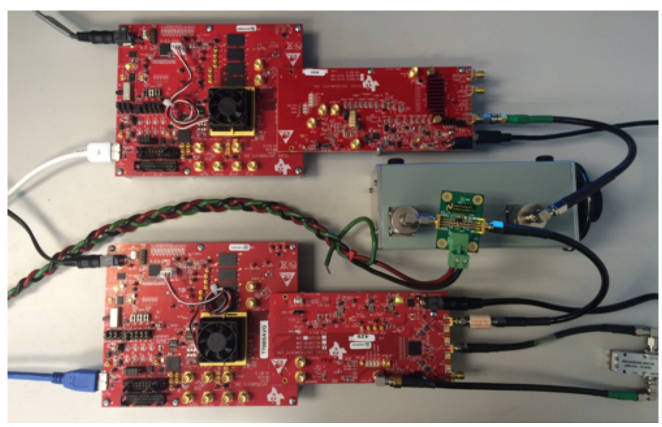
Features

- S-Band Transmitter Reference Design
- Wideband Frequency Flexibility and Planning
- Demonstration Using Multichannel Modulated Waveforms and Pulse Compression
- LFM and NLFM Waveforms Compatible With the National Weather Radar Testbed (NWRT)

Applications

- Weather Radar
- Air Traffic Control Radar
- Military Radar
- Wireless Communication Systems
- Radar-Based Level Sensing
- Radar-Based Distance Measurement





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1 System Overview

1.1 System Description

The TIDA-01240 reference design shows the use of direct RF sampling in radar transmitter applications. The focus of this application is radar operating in S-band (2 GHz to 4 GHz) where direct RF sampling is possible using the DAC38RF80 or DAC38RF83, 9-GSPS digital-to-analog converters (DACs). Direct RF sampling offers the advantage of a lower power and foot print signal chain while improving the flexibility of operation. This includes both the frequency of operation and support for operation of multiple simultaneous channels.

The aged US weather radar infrastructure, which are composed primarily of a network of NEXRAD (WSR-88D, S-band) units and supplemented by the airport-local terminal Doppler weather radar (TDWR, C-band) and airport surveillance radar (ASR family, S-band), relies on the transmission of high peak power pulses (750 kW, 250 kW, ASR-9 1300 kW respectively[1][2]) to achieve long-range detection (100 to 500 km) with a pulse duration on the order of 1 to 5 µs. These systems use cavity or tube power amplifiers (that is, kylstrons, magnetrons, TWTs) and transmit relatively simple pulse waveforms. Developments in solid-state (SS) power amplifiers achieving >100-W peak power are proliferating the use of full SS-transceiver designs using pulse-compression techniques to overcome the limitations of the lower peak output power[3]. A notable recent upgrade from airport surveillance radar model ASR-9 to ASR-11 abandons the use of a Klystron amplifier to use a bank of SS amplifiers that transmit a >10-µs pulse duration and uses pulse-compression processing at the receiver. The rise of SS-power amplifiers and performance available in today’s large volume cost structures has also renewed interest in large phase-array active antenna architectures, which has spurred the NOAA-sponsored NWRT[4], FAA-sponsored next-gen surveillance, and weather radar capability (NSWRC)[5] initiatives to evaluate the feasibility of a multifunction-phased array radar (MPAR) network that integrates the functions of the existing networks to simultaneously accommodate both weather and air traffic control requirements, as shown in Figure 1.

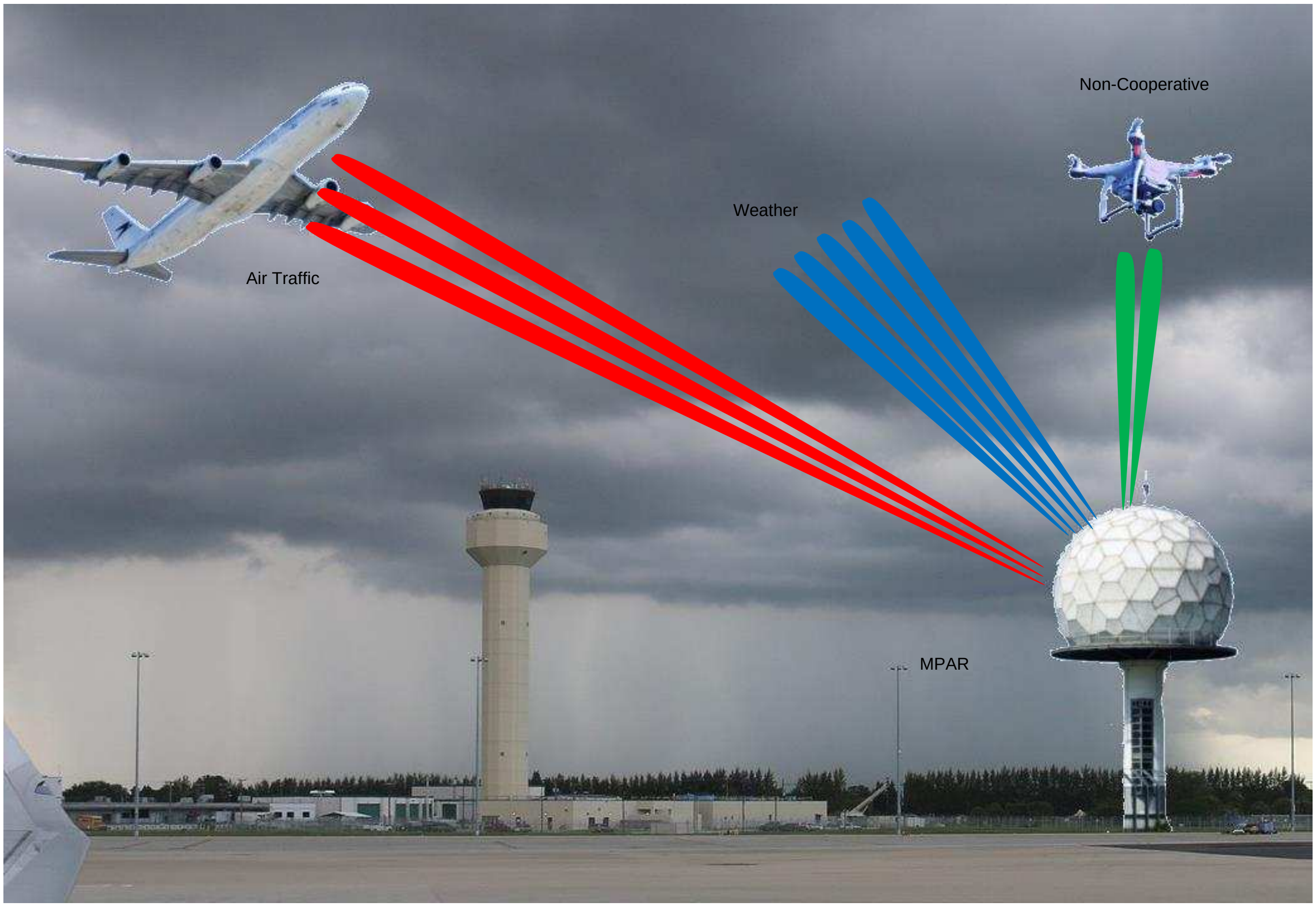

Figure 1. MPAR for Weather Sensing and Air Traffic Control

Greater societal interest in weather, severe weather tracking, and climate change has also motivated the development of medium range, fixed, and mobile radar platforms in a variety of operating bands that are using more sophisticated pulse-compression and signal processing techniques to stretch the operating range of the unit in a limited peak-transmit power environment. The use of pulse compression has numerous trade-offs and requirements related to weather radar detection of volumetric targets versus point targets, so flexibility in waveform generation for can be highly advantageous.

The requirements of the transmitter to be flexible in generating sophisticated, high-performance pulses for compression processing that can be upgraded to exploit advances in signal processing and even updated dynamically to adjust to atmospheric conditions suggests a more software-defined approach to radar signal generation and processing[3][6].

This TI Design discusses the use of a highly-channelizable RF sampling DAC architecture for direct RF synthesis of software-defined, high-performance pulse-compression waveforms suitable for use in an MPAR at S-band or enabling single-step translation to C-, X-, and Ku-bands.

1.2 Key System Specifications

Table 1. Key System Specifications

PARAMETER	SPECIFICATIONS	DETAILS
RF carrier frequency	2800 MHz and 2850 MHz	Section 2.4
Pulse type	Linear frequency modulation (LFM) and non-linear frequency modulation (NLFM)	Section 2.4
Pulse bandwidth	27 MHz	Section 2.4
LFM peak sidelobe level	-40 dB close in, -50 dB far out	Section 4.3
NLFM peak sidelobe level	-65 dB close in, -70 dB far out	Section 4.3

1.3 Block Diagram

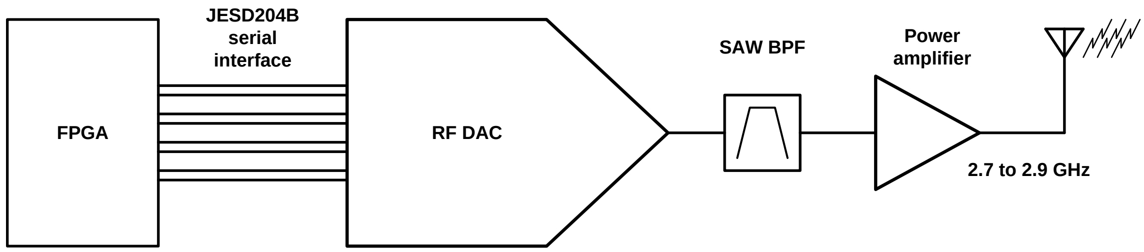

Figure 2. Block Diagram

1.4 Highlighted Products

1.4.1 DAC38RF80 or DAC38RF83 RF DACs

The DAC38RF80 and DAC38RF83 are dual-channel, 14-bit, 9-GSPS RF DACs with up to eight-lane, high-speed serial JESD204B interfaces. Complex baseband data is input at up to 1230 MSPS along SERDES lanes that transfer at up to 12.5 Gb/s, which allows over 1 GHz of input bandwidth. Each DAC channel has two digital up-converter (DUC) signal paths with independent NCOs and up to 24 times interpolation. An internal PLL accepts a reference and generates the 9-GHz conversion clock with low PLL phase noise. The DAC38RF80 has an internal balun that coverts the differential signal from the DAC core into a single-ended output at frequencies as high as 6 GHz. Figure 3 shows a block diagram of the device. The DAC38RF83 provides direct differential output of the DAC core for applications that do not require a balun transformer.

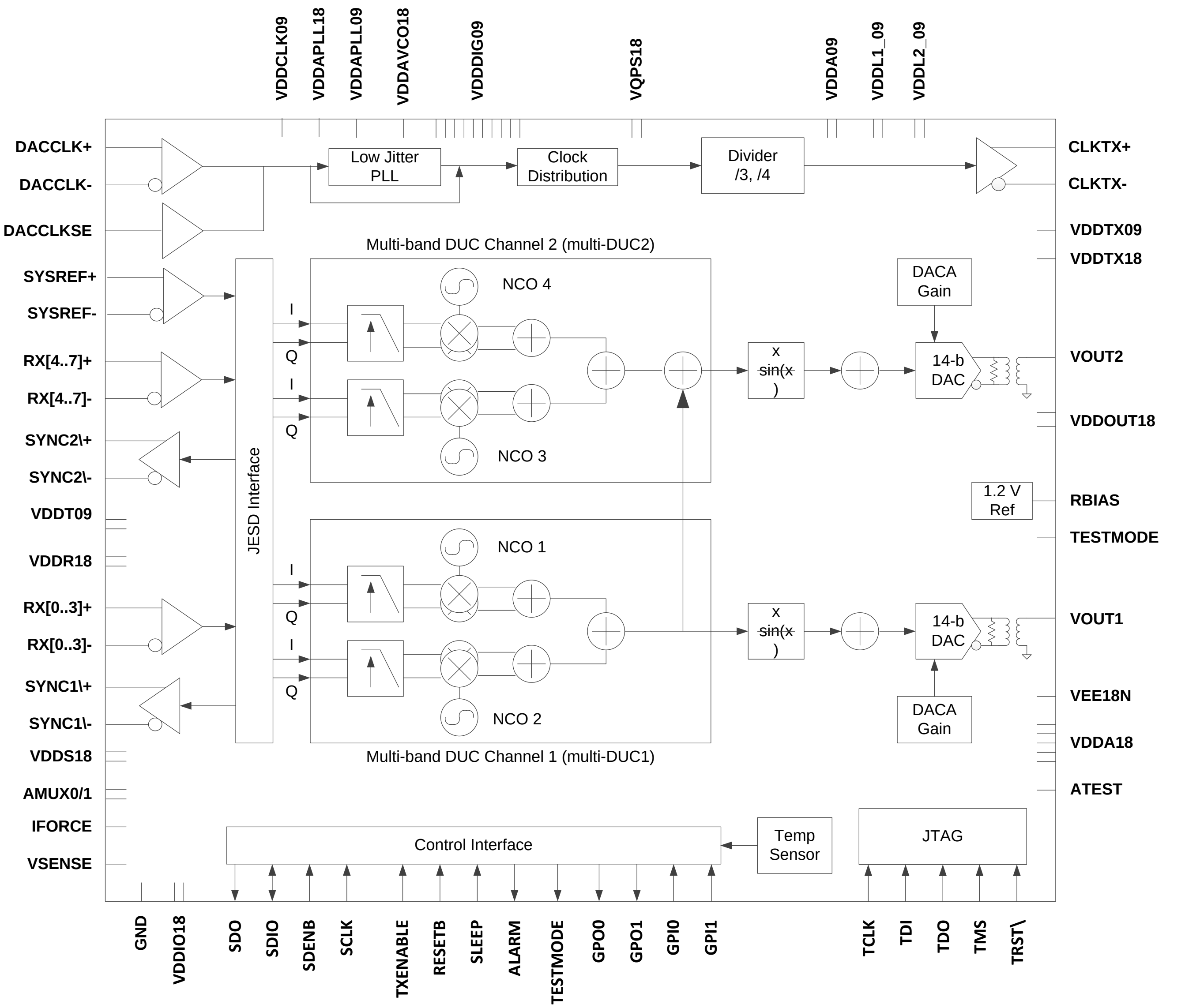

Figure 3. DAC38RF80 Block Diagram

2 System Design Theory

2.1 MPAR Transmitter

An MPAR accomplishes the following goals:

- Improved scan rate and reliability: leverages the phased-array technologies for non-mechanical beam steering.
- Multi-mission: consolidates multiple functions (such as weather detection and airport traffic control) into one unit, within one band, transmitted simultaneously on separate frequency channels.

Figure 4 shows the simplified transmitter array of a multifunction phased-array radar, which includes multiple channels of waveform generation for multi-mission capability, digital beamforming (with aggregated channels), digital-to-analog conversion, filtering, and power amplification.

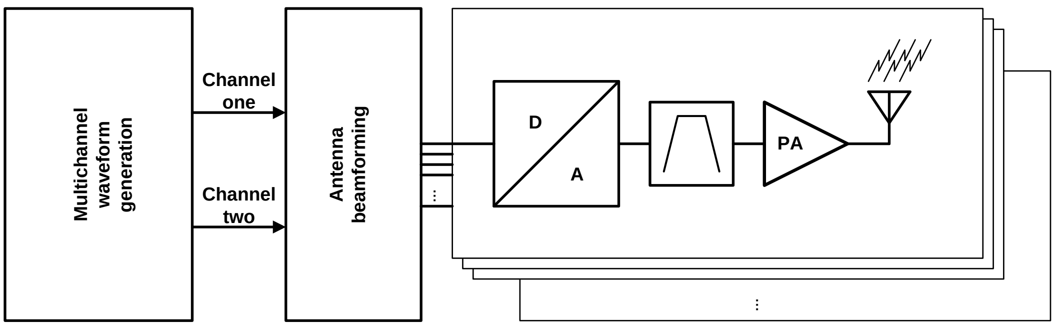

Figure 4. MPAR Transmitter With Digital Beamforming

2.2 RF Sampling DAC Direct Synthesis at S-Band

Traditional signal waveform transmission at S-band has used a homodyne (complex, zero-IF) or super-heterodyne architecture, which included mixing and filtering stages to translate the signal from baseband to the RF center frequency, as shown in Figure 5. Using an RF DAC in Figure 6, the frequency translation functions of the signal chain are shifted into the digital domain, which eliminates mixers, IF filters, and LOs (PLLs) from the analog-signal chain to achieve direct synthesis at the S-band where the critical frequencies for the MPAR are between 2.7 and 2.9 GHz.

The RF sampling architecture eases frequency planning, provides wider bandwidth, eliminates concerns over quadrature mixing from baseband, and reduces filtering requirements in the analog signal path.

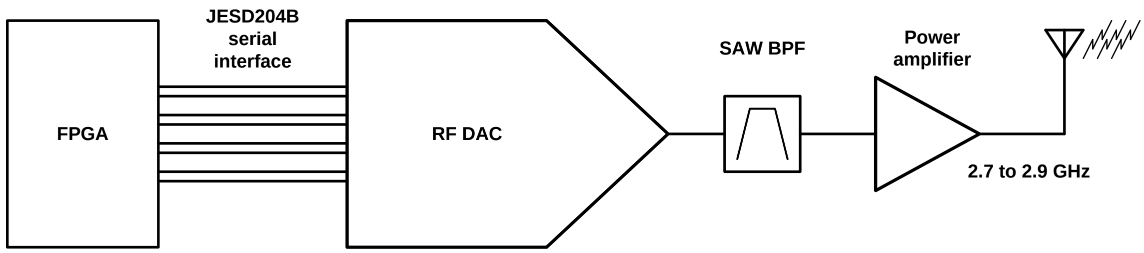

Figure 5. Direct Synthesis Using RF Sampling Transmitter Architecture

The development of the JESD204B serial data interface for data converters has also improved the ability to channelize high-speed DACs by reducing the number of data lanes (and therefore PCB real estate) required to transfer data, as seen with the RF DAC of Figure 6, which is critical for the large channel counts of phased-array radars.

2.3 Synthesis for C-, X-, and Ku-Bands

An RF DAC also simplifies the generation of signals at higher bands by reducing the number of required analog mixing stages thereby reducing the complexity of distortion and image mixing products.

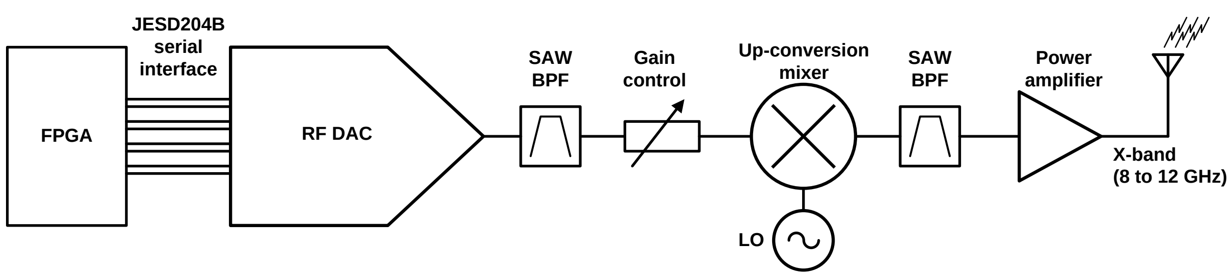

Figure 6. Single-Mixing Stage X-Band Transmitter

2.4 Pulse-Compression Waveforms and Trade-offs

Pulse compression relies on some form of modulation applied to a long duration signal with low peak power that, when received, is passed through a filter that performs correlation against the expected waveform over time. The output result is a large peak-power, short-time pulse that appears at the time instant when the received waveform is fully correlated with the expected. Many forms of modulation have been found to be useful including frequency, phase, and amplitude modulation. Each of these modulation types has tradeoffs that influence the radar performance, including:

- Pulse-compression ratio (and effective range resolution)
- Compressed pulse sidelobe level
- Signal-to-noise ratio (SNR) (and effective maximum range)
- Bandwidth of transmitted signal

Weather detection is a volumetric (as opposed to a point target) application that suffers from significant amounts of attenuation when propagating through severe weather systems, so it is critical to maximize SNR while, at the same time, minimizing the sidelobe levels created during compression to reasonable levels of < -65dBc[7]. Insufficiently low sidelobe levels cause range smearing of the weather target, which can distort the target size and derived precipitation predictions. Compression-sidelobe levels are not as critical in air traffic detection applications (< -40dBc)[8] although the very long range requirements even in the presence of weather puts emphasis on achieving good SNR. The available S-band transmission band from 2.7 to 2.9 GHz is limited and is often shared between multiple functions, so the bandwidth available for modulation is confined.

LFM, NLFM, and mismatched filtering for sidelobe optimization are effective techniques for weather applications. This TI Design uses two adjacent frequency channels to accomplish separate missions as described in Table 2. Channel two uses a standard LFM waveform for long-range airplane detection and a mismatched filter receiver with low-SNR loss for long-range detection, but the channel has poor sidelobe performance. Channel one uses the NLFM waveform for weather storm measurements and transmits a constant envelope power, but the channel has a mismatched receiver filter with amplitude shaping. Both the non-linear modulation and mismatched filter work together to reduce the sidelobes to below –70 dBc at the cost of 3-dB SNR loss and 2× reduction in the compression ratio as a result of the windowing function incorporated into the mismatched filter. Both channels have a 10-µs pulse length and use 27 MHz of bandwidth, which yields time-bandwidth product of BT = 270. Channels are spaced 50-MHz apart to ensure minimal cross-correlation between channels.

Table 2. Multi-Mission Waveforms

PARAMETER	CHANNEL 1	CHANNEL 2
Mission	Weather storm measurements	Long-range airplane detection
Signal type	NLFM	LFM
Bandwidth (3 dB)	27 MHz(1)	27 MHz
Total bandwidth (10 dB)	77 MHz	
Center frequency	2800 MHz	2850 MHz
Pulse duration	10 µs	
Rx detection filter	Mismatched (Blackman-Harris window amplitude tapering)	Mismatched (Hamming window amplitude tapering)
Filter output sidelobe level (ideal)	–78 dBc	–40 dBc
SNR loss (Ideal)(2)	3 dB	1.3 dB
Compression ratio (first null)	77	230

(1) The reported NLFM bandwidth is the actual 3 dB used spectral bandwidth and does not indicate the full span of the non-linear frequency range.
(2) SNR loss is due to the use of the mismatched filter, a technique used for sidelobe suppression, and is equal to the processing gain of the windowing function used in the filter for amplitude tapering.

2.5 Generating Waveforms With RF DAC

Each DAC channel of the DAC38RF80 or DAC38RF83 has a dual-path DUC that can be used to aggregate channels. In this application, each DUC path accepts 16-bit complex IQ data at 368.64 MW/s and interpolates by 24x, up-converts the channels to their respective RF frequencies using independent NCOs, and then adds the channels together before DAC conversion. Inverse sinc shaping is used in the digital signal path to correct the zero-order hold output frequency shaping of the DAC. The DAC output conversion rate is 8.84737 GS/s. The signal is output in the first Nyquist zone of the DAC and is chosen to avoid HD2 and HD3 regions This placement allows adequate space between the channel and second Nyquist image band, as shown in Figure 7. The relaxed frequency planning is enabled by the frequency multiplying PLL inside the RF DAC to generate the approximately 9-GPSP conversion rate. Outputting directly in the 2.7- to 2.9-GHz frequency band is well within the output RF bandwidth of the DAC38RF80 or DAC38RF83.

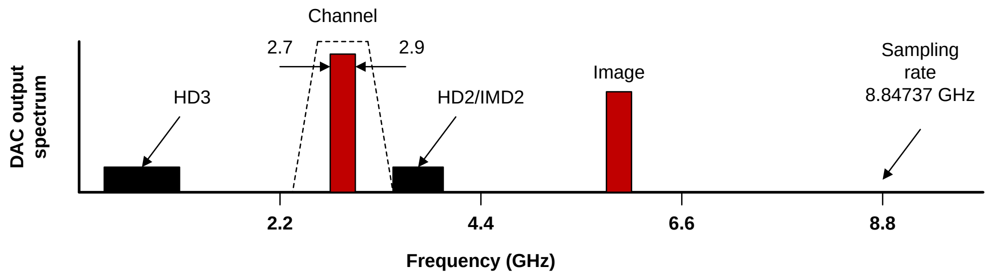

Figure 7. RF DAC Frequency Plan for 2.7- to 2.9-GHz Channel

3 Getting Started Hardware

3.1 Multichannel Chirp Waveform Measurement

The goal of this measurement is to generate the multi-mission aggregate waveform with the RF DAC, receive the signal, and digitally process (through MATLAB®) the individual channels with their respective pulse-compression filters to observe the quality of the compressed waveform.

3.1.1 Measurement Setup

The DAC38RF8xEVM is used to generate the waveform, and a high-performance RF sampling receiver ADC (ADC32RF45EVM) is used to receive the multichannel signal. The ADC device samples directly at 2949.12 MSPS, and the pulse is converted to baseband and decimated by 8× during post-processing of a full pulse. TSW14J56EVM FPGA boards are used for data transfer between the computer and the signal path TX and RX boards. Exact synchronization between the TX and RX boards is normally required in an application but is not strictly required for the purpose of this experiment as the frequency mismatch results in a static frequency offset at the receiver similar to a Doppler shift, which is within the expected behavior of the application and system. The simplified system diagram is shown in Figure 8.

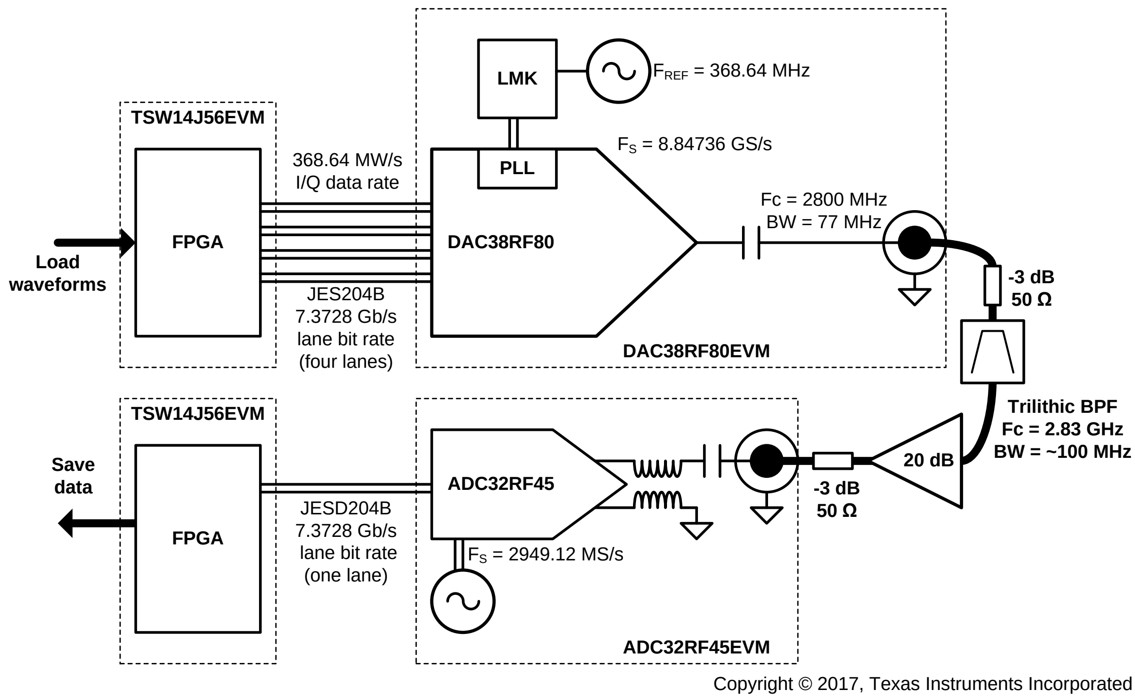

Figure 8. Measurement Test Setup

Figure 9 shows the test hardware setup.

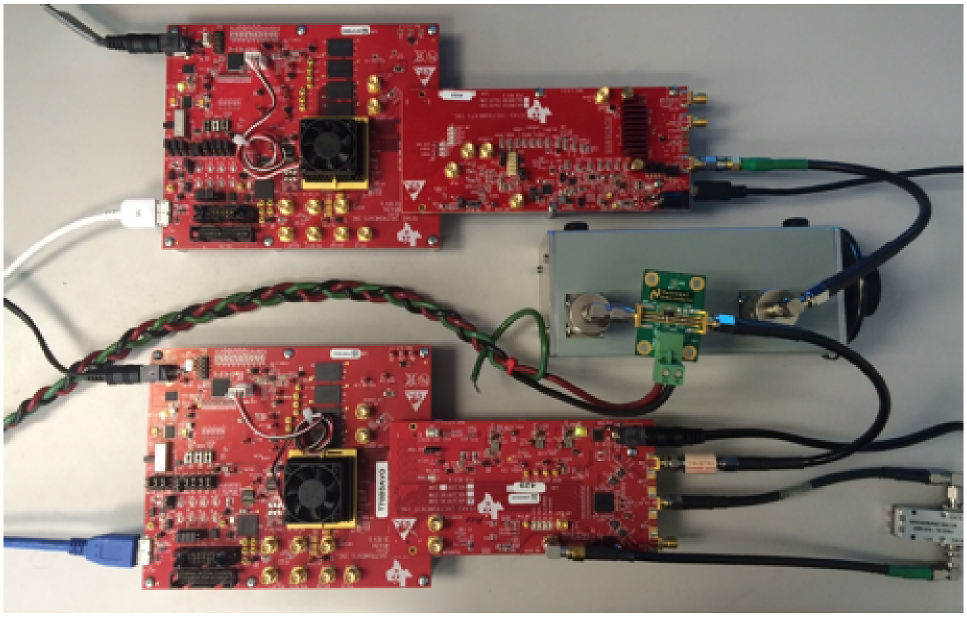

Figure 9. Test Hardware

4 Testing and Results

4.1 Chirp Waveforms and Frequency Profile (Ideal)

The two mission waveforms both use constant envelop frequency modulated chirp waveforms whose baseband representations are shown in Figure 10. The channel two LFM waveform has a linear frequency ramp, whereas the channel one NLFM waveform uses a frequency ramp with sharply accelerated deviations at the start and end of the waveform similar to that developed by De Witte and Griffiths[9].

Digital filtering is performed on each of the waveforms to confine the bandwidth so that the channels may be closely spaced in the spectrum with the 50-MHz spacing shown in Figure 11. Due to its large frequency deviations, the NLFM chirp requires approximately 1.3 times larger bandwidth than the LFM waveform to accommodate the frequency response transition bands as required for the desired sidelobe performance. Care is taken to use digital filtering that preserves the sidelobe performance and provides a small amount of waveform envelope rise and fail time while avoiding under-damped ringing during the transitions. Figure 10 shows the summed aggregate waveform at baseband.

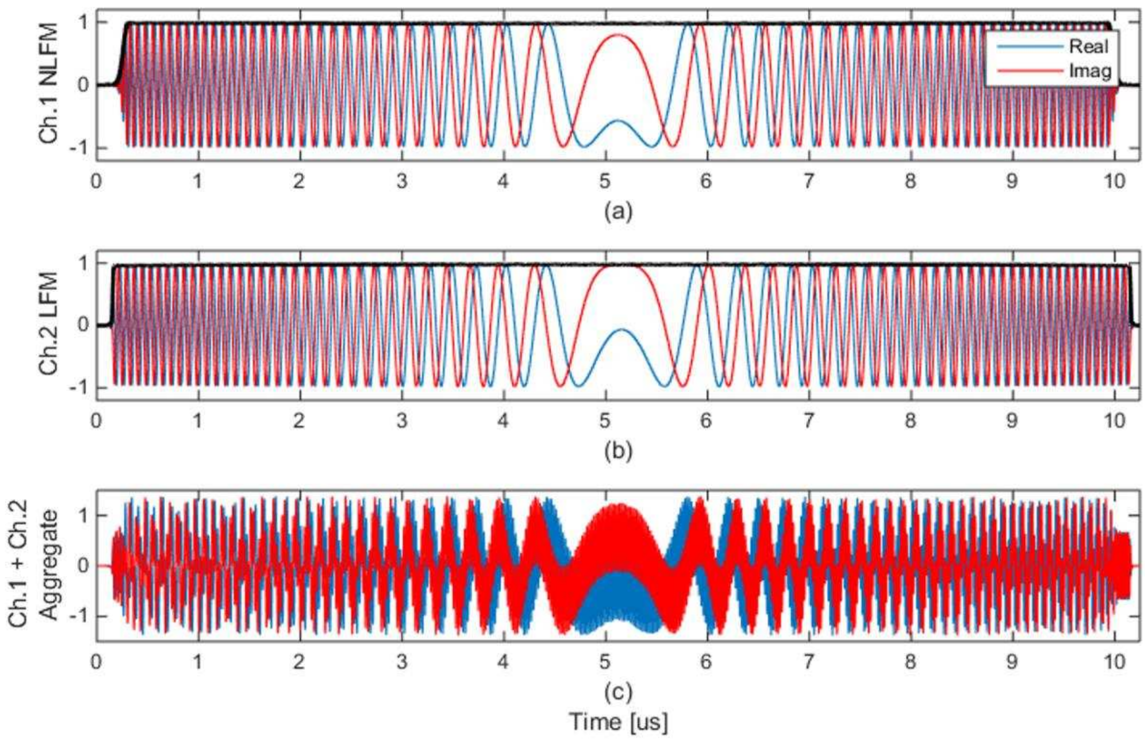

Figure 10. Chirp Waveforms (Ideal)

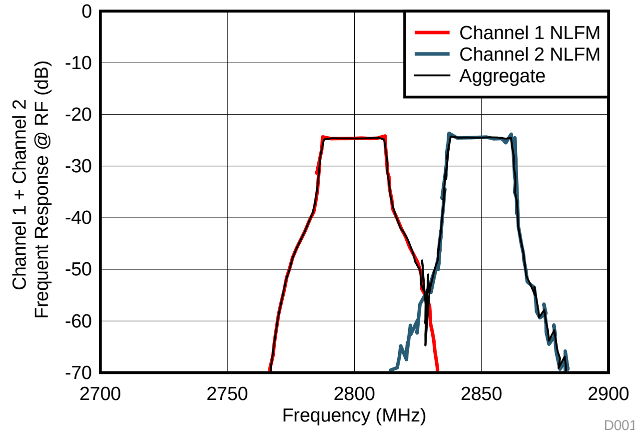

Figure 11. Aggregate Signal Frequency Response at RF (Ideal)

4.2 Measured Frequency Response

Figure 12 shows the frequency response of the RF DAC output, as measured with a spectrum analyzer.

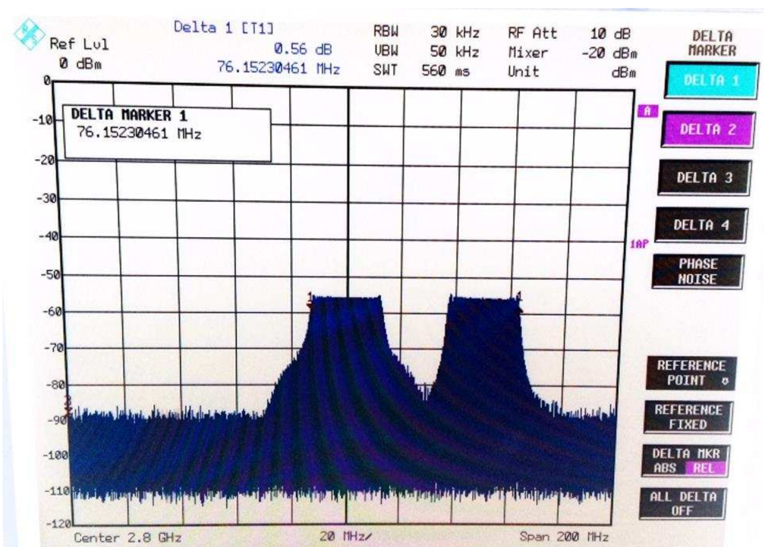

Figure 12. Measured Transmit Bandwidth

4.3 Measured Pulse-Compression Filter Outputs

The output of the compression filters with measured data stimulus for both channels is shown in Figure 13 with two views for observation of the far-out and in-close sidelobes. Compression of the channel two LFM waveform matches well with expected results at –50-dBc far-out and –40-dBc close-in peak sidelobe levels (PSL), which are artifacts of the chosen waveform and compression filter strategy. The channel one NLFM compression performance is not dictated by the waveform and filter choice, rather the compression performance is limited by the performance of the analog signal path, particularly the DAC's IMD3 and phase noise of the internal PLL. Despite the noise and distortion limitations, the close-in PSL is less than –65 dBc as desired, and far-out PSL quickly rolls off to below –70 dBc. With the given NLFM waveform, the in-close PSL performance has potential for improvement by using the external clock source option of the RF DAC.

As can be seen with the zoomed-in view of Figure 13, the LFM waveform outperforms the NLFM with a finer range resolution as a result of its narrower main lobe. Although it is not apparent with the amplitude normalized y-axis of Figure 13, channel one has 1.7-dB better SNR performance than channel two due to the use of less-aggressive amplitude tapering in its pulse-compression filter.

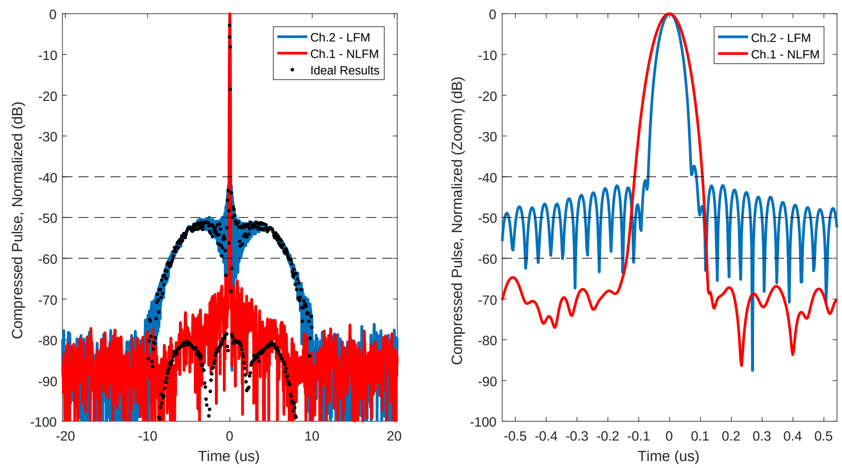

Figure 13. Measured Output of Pulse-Compression Filters

4.4 Conclusion

The DAC38RF80 or DAC38RF83 RF sampling DACs are demonstrated as an effective direct RF synthesis solution for the synthesis of multichannel frequency modulated chirp waveforms at S-band, which show performance acceptable for weather and air traffic control applications. The direct synthesis, performance, and highly-channelizeable architecture of the device make these RF DACs suitable for a MPAR application and for displacing traditional super-heterodyne signal path architectures in general.

5 Design Files

5.1 Schematics

To download the schematics, see the design files at TIDA-01240.

5.2 Bill of Materials

To download the bill of materials (BOM), see the design files at TIDA-01240.

5.3 PCB Layout Recommendations

5.3.1 Layout Prints

To download the layer plots, see the design files at TIDA-01240.

5.4 Cadence Project

To download the Cadence project files, see the design files at TIDA-01240.

5.5 Gerber Files

To download the Gerber files, see the design files at TIDA-01240.

5.6 Assembly Drawings

To download the assembly drawings, see the design files at TIDA-01240.

6 Related Documentation

1. Wolff, Christian. *Radar Tutorial*. Accessed July 21, 2016.
2. *FAA Weather Systems*. MIT Lincoln Laboratory: FAA Weather Systems: Terminal Doppler Weather Radar. Accessed. Accessed July 21, 2016.
3. Cheong, Boon Leng, Redmond Kelley, Robert D. Palmer, Yan Zhang, Mark Yeary, and Tian-You Yu. *PX-1000: A Solid-State Polarimetric X-Band Weather Radar and Time–Frequency Multiplexed Waveform for Blind Range Mitigation*. IEEE Transactions on Instrumentation and Measurement 62, no. 11 (2013): 3064-072. doi:10.1109/tim.2013.2270046.
4. *Multi-Function Phased Array Radar*. NOAA National Severe Storms Laboratory. Accessed July 21, 2016.
5. Hondl, Kurt D., *Multi-Function Phased Array Radar (MPAR)*. National Weather Center, (February 2015).
6. Meier, John, Redmond Kelley, Bradley M. Isom, Mark Yeary, and Robert D. Palmer. *Leveraging Software-Defined Radio Techniques in Multichannel Digital Weather Radar Receiver Design*. IEEE Transactions on Instrumentation and Measurement 61, no. 6 (2012): 1571-582. doi:10.1109/tim.2011.2178670.
7. Palmer, Robert, Boon Leng Cheong, Joseph Havlicek, Howard Bluestein, and Guifu Zhang. *Pulse Compression Waveforms and Applications for Weather Radar*. Kurdzo, James. October 19, 2015. Accessed 21 July 2016.
8. Weber, M. E. *Wind Shear Detection Using the Next Generation Airport Surveillance Radar (ASR-11)*. National Technical Information Service (1999).
9. Witte, E. D., and H.D. Griffiths. *Improved ultra-low range sidelobe pulse compression waveform design*. Electronics Letters 40, no. 22 (2004): 1448. doi:10.1049/el:20046548.

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