100 MS/s, 16-bit Arbitrary Waveform Generator with Onboard Signal Processing

NI PXI-5441

- Quadrature digital upconversion
- FIR and CIC interpolation filters
- Carrier frequencies up to 43 MHz with 355 nHz resolution
- 16-bit resolution, 100 MS/s sampling rate
- 400 MS/s effective sampling rate with DAC interpolation
- 32, 256, 512 MB of onboard memory
- Multimodule synchronization with < 20 ps_{rms} skew
- Continuous data streaming up to 100 MB/s

Operating Systems
- Windows 2000/NT/XP

Recommended Software
- LabVIEW
- LabWindows/CVI
- SignalExpress
- Measurement Studio
- Digital Filter Design Toolkit

Included Software
- NI-FGEN driver
- LabVIEW Express VIs
- NI Modulation Toolkit
- NI Analog Waveform Editor
- FGEN Soft Front Panel
- LabVIEW RealTime Support

Calibration
- Gain and offset self-calibration
- 2 year external calibration cycle

NEW

Overview
The National Instruments NI PXI-5441 is a 100 MS/s arbitrary waveform generator with Onboard Signal Processing (OSP). OSP functions include FIR and CIC interpolation filters, digital per-filter gain and offset control, a numerically controlled oscillator (NCO) and IQ mixing for quadrature digital upconversion. With 16-bit resolution and -91 dBc close-in spurious free dynamic range (SFDR), the PXI-5441 brings instrument quality specifications to applications requiring digital upconversion and baseband interpolation such as prototyping, validating, and testing communications, radar, and electronic warfare systems. Since the PXI-5441 is a full-featured arbitrary waveform generator, it is also capable of generating general purpose electrical test signals and has a maximum output range of 12 V_{pk-pk} into a 50 Ω load.

By using the PCI bus to communicate with the host computer, the PXI-5441 can download waveforms at up to 100 MB/s, far faster than traditional GPIB-based instruments. Using the Synchronization and Memory Core (SMC) architecture of the PXI-5441, you can create mixed signal test systems by synchronizing the generator with digitizers and digital waveform generator/analyzers or synchronize multiple generators to form a phase-coherent multi-channel generator for generating I/Q signals for applications such as MIMO (multiple-input multiple-output) or beam-forming antenna schemes.

Onboard Signal Processing
Onboard signal processing (OSP) (Figure 1) significantly extends waveform playback time and reduces the time required to compute and download waveform data by computing the waveform data using the PXI-5441’s field programmable gate array (FPGA). OSP delivers several signal processing functions used to modify the data stored in waveform memory during generation. The signal processing functions are:

Independent I and Q pre-filter gain and offset
For adding gain and offset imbalance impairments, I and Q pre-filter gain and offset can be adjusted before or during the generation of an output signal.

Finite impulse response (FIR) filter
The FIR filter shapes the waveform data, compensates for the cascaded-integrator comb (CIC) filter response, and interpolates the waveform data by 2, 4, or 8x. The FIR filter coefficients are programmable and include flat, raised cosine, root raised cosine, Gaussian, or custom. For implementing custom filters, consider the NI Digital Filter Design Toolkit which includes several advanced filter design tools for designing, analyzing, and simulating floating-point and fixed-point filters.

Cascaded-integrator comb (CIC) filter
For upsampling waveform data to a high sample rate, the CIC filter efficiently interpolates by 6x to 256x.

Numerically controlled oscillator (NCO)
The NCO produces sine and cosine waveform data for quadrature digital upconversion and features 355 nHz frequency resolution and 0.0055° phase resolution for precise control of impairments such as frequency error and quadrature skew. NCO frequency and phase can also be adjusted before or during waveform generation.

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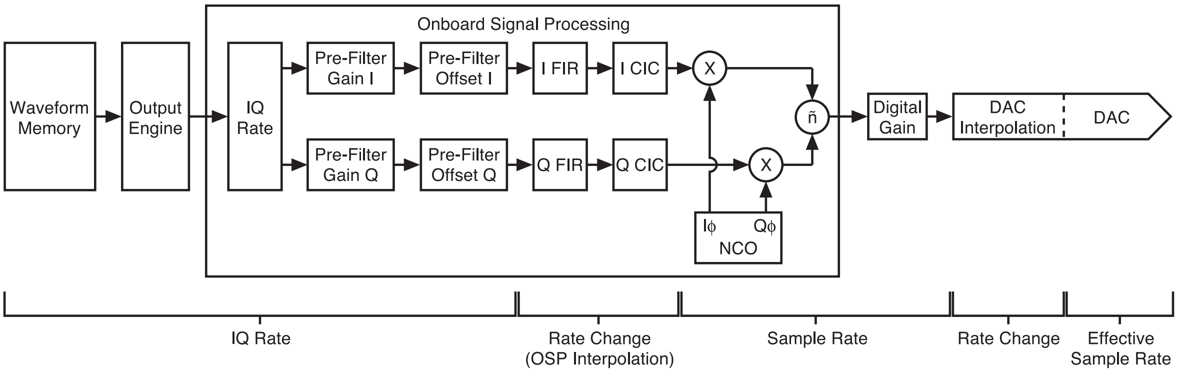

Figure 1. Onboard Signal Processing uses the PXI-5441's FPGA to perform in-line processing of the waveform data stored in the module's memory.

In addition to being an arbitrary waveform generator with waveform sequencing capability, the PXI-5441 uses the OSP functions to perform:

Quadrature digital upconversion with impairments

In quadrature upconversion, I and Q complex waveform data is stored in waveform memory and is passed to the OSP block. OSP then shapes and interpolates the data using the FIR filters, interpolates it up to a high sample rate using the CIC filters, and then upconverts the data to a programmable carrier frequency up to 43 MHz. You can choose to suppress the lower or upper modulation sideband by adjusting the NCO in-phase and quadrature output phase settings.

For modeling channel effects and testing the robustness of a receiver, the OSP can add several impairments to the signal on the fly (during waveform generation). IQ Gain Imbalance and DC offset impairments are added by adjusting the per-filter gain and offset settings, while quadrature skew and frequency error can be introduced by adjusting the I or Q carrier phase and frequency.

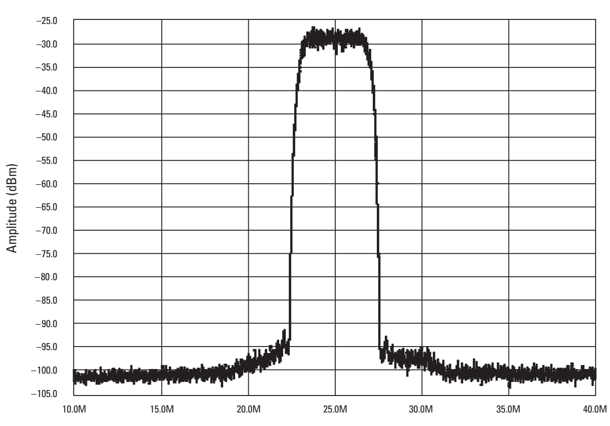

Figure 2. Frequency spectrum of a W-CDMA physical layer signal digital upconverted and generated by the PXI-5441 with Onboard Signal Processing. (External sample clock = 92.16 MHz)

Baseband interpolation

Useful for generating smooth baseband signals, such as I and Q signals, you can use the PXI-5441's OSP block to interpolate low sample rate waveforms to a much higher sample rate, thereby improving the output frequency spectrum by relocating zero-order sample-and-hold reconstruction images to higher frequencies. With the images at higher frequencies, the PXI-5441's 7th order low-pass analog filter can greatly suppress them without disturbing the signals' amplitude response or phase information. For example, a waveform created at 10 kS/s sample rate could be interpolated to 10.24 MS/s by using 4x FIR interpolation and 256x CIC interpolation. The upsampled signal is then passed to the DAC which can also interpolate by 2, 4, or 8x resulting in an effective sampling rate of 81.92 MS/s (8x DAC interpolation). Since the original waveform was sampled at only 10 kS/s, rather than 81.92 MS/s, a 1:8,192 compression ratio is achieved, resulting in dramatically faster waveform computation and download times. Alternatively, the resulting compression can be used to efficiently store data in the PXI-5441's onboard memory allowing for much longer playback times without streaming from arrays of high-speed disk drives. Long playback times are essential for improving the statistical significance of many communications measurements and displays such as bit error rate, trellis plots, and constellation plots.

Amplitude modulation (AM)

By using only the in-phase (I) path of the OSP block, you can generate an AM radio signal by directly downloading the message signal into onboard memory. The message signal scales the amplitude of the NCO's programmable frequency output.

Single tone and function generation

Using the OSP block's NCO, the PXI-5441 can generate sine, square, triangle, ramp and other standard and user-defined waveforms just as function generator does. The frequency of the output waveform may be adjusted during generation with 355 nHz resolution for generating phase continuous frequency sweeps and hops. The phase is also adjustable relative to other synchronized instruments, the PXI 10 MHz reference clock or an externally supplied reference clock.

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DAC Interpolation

The NI 5441 uses digital interpolation to improve the output signal quality of smooth waveforms. Every digital-to-analog converter (DAC) produces reconstruction images in the frequency domain as a result of the conversion process. Appearing at $|f_o \pm nf_s|$, where f_o is the frequency of the desired signal and f_s is the sampling rate, reconstruction images are undesirable for smooth signals, such as sine waves.

Typically, arbitrary waveform generators suppress the reconstruction images by using high-order low-pass filters with a cutoff frequency near the generator's Nyquist frequency (50 MHz for a 100 MS/s sample rate). By using a high-order filter with such a low cutoff frequency, the filter's non-idealities, such as passband ripple and non-linear phase significantly affect the generator's performance. The NI 5441 uses digital interpolation to increase the effective sample rate, relocating the reconstruction images to higher frequencies.

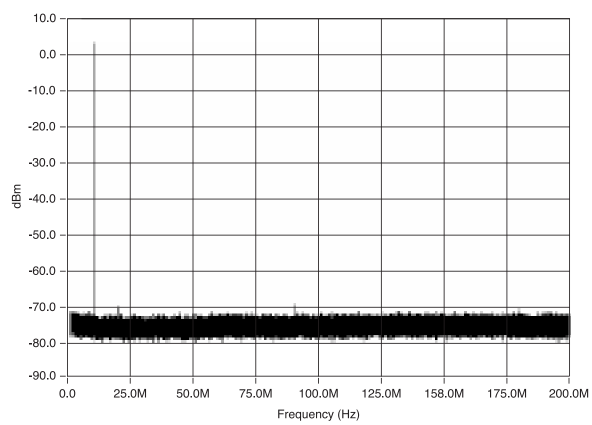

Figure 3. Using a combination of digital interpolation and analog filtering, the NI 5441 greatly reduces the DAC reconstruction images as shown for the 10 MHz sine signal generated at 100 MS/s using 4x interpolation for a 400 MS/s effective sampling rate. (Noise floor is limited by the measurement device.)

By doing so, the required analog filter cutoff frequency is increased which lessens the filter's distortion effects. The combination of digital interpolation and analog filtering enable the NI 5441 to have excellent passband flatness and improved image rejection ensuring a low-distortion output signal.

For sharp waveforms, such as square waves, pulses, and video signals, interpolation and analog filtering can be disabled resulting in fast rise/fall times and low pulse aberration (overshoot, undershoot, etc).

Waveform Sequencing and Triggering

The NI 5441 can be programmed to sequence and loop a set of waveforms. Several methods can be used to advance through the sequence of waveforms. In some cases, the duration of each waveform is known in advance, so the generator can be programmed to loop each waveform a specified number of times. When the duration is unknown before generation, a hardware or software trigger can advance the generator to the next waveform in the sequence. The NI 5441 implements advanced triggering behavior with four trigger modes: single, continuous, burst, and stepped. For a detailed discuss of these modes, please consult the NI Signal Generators Help Guide available at **ni.com/manuals**.

Waveform 1	Waveform 2	• • •	Waveform n	Sequence Instructions 1	Sequence Instructions 2	• • •	Sequence Instructions m	Free Memory

Figure 4. NI's SMC-based arbitrary waveform generators increase test throughput by storing all the waveforms and sequences required for a set of test in onboard memory.

NI's SMC-based generators have the unique capability to store multiple sequences and their associated waveforms in the generator's onboard memory (Figure 4). In automated test situations involving multiple tests each requiring a different waveform sequence, all of the sequences and waveforms can be downloaded once at the beginning of the test cycle and held in the generator's memory for the entire session. By downloading all required waveforms and sequences once, instead of repeatedly reloading them for each test, the SMC-based generators save test time and improve test throughput.

Timing and Synchronization

Using T-Clock synchronization technology, multiple NI 5441's can be synchronized for applications requiring a greater number of channels, such as I/Q signal generation or multiple IF generation for MIMO systems. Since it is built into the SMC, T-Clock can synchronize the NI 5441 with SMC-based high-speed digitizers and digital waveform generator/analyzers for tight correlation of analog and digital stimulus and response. Using onboard calibration measurements and compensation, T-Clock can automatically synchronize any combination of SMC-based modules with less than 500 ps_{rms} module-to-module skew. Greatly improved from traditional synchronization methods, the skew between modules does not increase as the number of modules increases. To achieve even better performance, a high-bandwidth oscilloscope can be used to precisely measure the module-to-module skew. Using the oscilloscope measurement for calibration information, T-Clock can achieve < 20 ps_{rms} module-to-module skew (Figure 5).

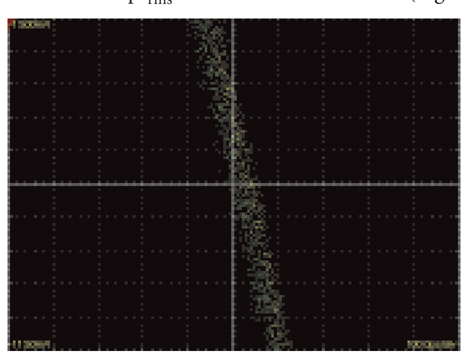

Figure 5. Using the Synchronization and Memory Core's T-Clock synchronization, multiple NI 5441 can achieve less than 20 ps channel-to-channel skew.

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The NI 5441's sample clock has three modes: Divide-by-N, High-Resolution, and External. The direct digital synthesis (DDS) based high-resolution sample clock has a sample rate resolution of 1.06 μHz. This offers you exceptional stability and sampling rate flexibility. The NI 5441 can also import its sample clock from the CLK IN, PXI star trigger and PXI trigger bus. In addition, you can phase lock the NI 5441's oscillator to an external reference or the PXI 10 MHz reference clock.

Driver Software

Accurate, high-throughput hardware improves the performance of a measurement system, but easy-to-use, reliable software reduces your development time and ongoing support costs. NI-FGEN, the driver software for the NI 5441, is the world's most advanced and thoroughly tested arbitrary waveform generator software and features:

- **Intuitive application programming interface (API)** – In LabVIEW, LabWindows/CVI, VisualBasic and Visual C/C++, NI-FGEN's API is engineered to use the least number of function's possible while also maintaining flexibility. Each driver function has thorough online searchable documentation. The NI-FGEN Quick Reference Guide further simplifies programming by providing an overview of each driver function's LabVIEW icon, function name, parameters, and data types.

- **LabVIEW Express VIs** – For generating an arbitrary repetitive signal, the LabVIEW Express VI is a configuration driven way to program the NI 5441 without accessing the underlying NI-FGEN functions.

- **Function generator mode** – Using the OSP's numerically controlled oscillator, the PXI-5441 can behave as an arbitrary function generator with 355 nHz frequency resolution. Using function generator mode, you can generate phase continuous frequency sweeps and hops.

- **Soft front panel** – For quick non-programmatic use of the NI 5441, the soft front panel supports arbitrary waveform and standard waveform generation.

- **Example programs** – NI-FGEN provides 23 programming examples for LabVIEW, LabWindows/CVI, VisualC++ 6.0 and .Net, and VisualBasic 6.0 so you don't have to start from scratch.

- **LabVIEW Real-Time Support** – For remotely deployed autonomous measurement systems or applications requiring the highest possible reliability, NI-FGEN supports LabVIEW's Real-Time module.

Modulation Toolkit for LabVIEW[1]

The Modulation Toolkit for LabVIEW provides functions for signal generation, analysis, and visualization of custom and standard analog and digital modulation. With the Modulation Toolkit, you can also develop and analyze custom modulation formats and generate these with the PXI-5441. Some of the standard measurement functions include EVM (error vector magnitude), MER (modulation error ratio), and ρ (rho). Functions are also available for injecting impairments including IQ Gain Imbalance, Quadrature Skew, and AWGN (additive white Gaussian noise). Visualization functions include trellis, constellation, and 2D- and 3D-eye diagrams. This hardware and software combination gives you access to customizable functionality not available in traditional instrumentation.

Modulation/Demodulation
- 4, 8, 16, 32, 64, 128, 256-QAM
- 2, 4, 8, 16-FSK
- MSK and GMSK
- 8, 16, 64-PSK
- BPSK, QPSK, OQPSK, DQPSK, $\frac{\pi}{4}$DQPSK
- AM, FM, PM

Modulation Analysis Functions
- ρ (rho)
- DC offset
- Phase error
- Quadrature skew
- IQ gain imbalance
- Bit error rate (BER)
- Frequency deviation
- Burst timing measurements
- Modulation error ratio (MER)
- Error vector magnitude (EVM)

Visualization and Analysis
- Trellis diagrams
- Constellation plot
- 2D- and 3D-eye diagrams

Modulation Impairments
- Multitone
- DC offset
- Fading profile
- Frequency offset
- Quadrature skew
- IQ gain imbalance
- Additive White Gaussian Noise (AWGN)

[1]A Modulation Toolkit datasheet is available separately.

Analog Waveform Editor[1]

The NI Analog Waveform Editor is an interactive software tool for creating and editing analog waveforms. In the editor, each waveform is comprised of different segments, where each segment is comprised of a collection of "primitives". You can create a new waveform segment by selecting from a library of over 20 waveform "primitives" (Table 1), by entering a mathematical expression, or importing data from a file. Waveform primitives can then be combined point-by-point using addition, multiplication, or division to create more complex segments (Figure 6).

[1]An Analog Waveform Editor datasheet is available separately.

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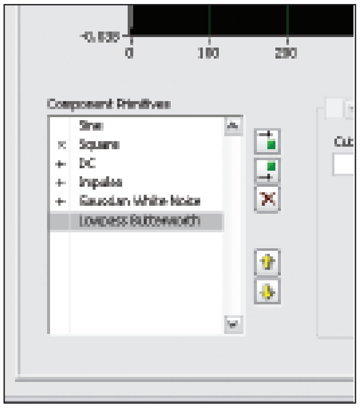

Figure 6: Over 20 different waveform primitives can be combined to create more complex waveforms.

Multiple segments can then be concatenated to make a larger waveform. To further process the waveform, you can apply standard or custom FIR and IIR filters or smooth any discontinuities between different waveform segments. Once complete, all the settings you chose to create the waveform are stored alongside the waveform's raw sample data, making it easy to reload the waveform in the editor and modify the settings of a particular segment or primitive.

Waveform Primitives

Sine	Triangular Noise	Trapezoid
Square	Gaussian Noise	Stairstep
Triangle	Sinc	Haversine
Sawtooth	Gaussian Pulse	Impulse
Uniform Noise	Exponential Rise/Decay	Cardiac

Table 1: A partial list of the configurable waveform primitives available in the Analog Waveform Editor.

Ordering Information

NI PXI-5441 ....779058-0M[1]

[1]M (onboard memory): 2 (32 MB), 3 (256 MB), 4 (512 MB)
Includes SMB 112 cable, NI-FGEN driver, FGEN Soft Front Panel, NI Modulation Toolkit for LabVIEW, and NI Analog Waveform Editor

Recommended PXI Switch

NI PXI-2593 778793-01

BUY NOW!

For complete product specifications, pricing, and accessory information, call (800) 813-3693 (U.S. only) or go to **ni.com/xxx**.

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Specifications

General

Number of channels 1
DAC Resolution .... 16 bits
Maximum Sample Rate .... 100 MS/s
Maximum Effective
Sample Rate with Interpolation .... 400 MS/s
Bandwidth .... 43 MHz
Output Paths
- 1 Main Output Path setting with driver selected Low Gain Amplifier or the High Gain Amplifier
- 2 Direct Path optimized for IF applications

Onboard Signal Processing (OSP)

Operating Modes .... Function generator, interpolating (I path only), quadrature digital upconversion (complex)
IQ Rate
- OSP Interpolation Range .... 12 to 2,048

Maximum IQ Rate .... 8.3 MSymbols/s
Pre-Filter Gain and Offset
- Pre Filter Gain and Offset Resolution .... 18 bits
- Pre-Filter Gain Range .... -2 to 2
- Pre-Filter Offset Range .... -1 to 1

FIR (Finite Impulse Response) Filter
- Filter Length .... 95 Taps
- Interpolation Range .... 2, 4, or 8
- Filter Types .... Flat, Gaussian, Raised Cosine, Root Raised Cosine, Custom Coefficents

CIC (Cascaded Integrator Comb) Filter
- Size .... 6 Stages
- Interpolation Range .... 6 to 256

NCO (Numerically Controlled Oscillator)
- Max Frequency Range .... 1 mHz to 43 MHz
- Max Frequency Resolution .... 355 nHz
- I and Q Phase Resolution .... 0.0055°

Modulation Performance (Typical)

	GSM PHY Layer	W-CDMA PHY Layer	DVB PHY Layer
Modulation Error Ratio (MER)	46 dB	46 dB	43 dB
Error Vector Magnitude (EVM)	< 0.5% $_{rms}$	< 0.5% $_{rms}$	0.6% $_{rms}$
Adjacent Channel Power Ratio (ACPR)	-	61 dBc	48 dBc

FIR interpolation = 2, direct path, 25 MHz carrier, external sample clock

Digital Performance
- OSP Out of Band Suppresion .... 74 dB (FIR Interpolation = 4)
- OSP Passband Ripple .... 0 to -0.08 dB (FIR Interpolation =2)

Function Generation Mode

Standard Waveform Max Frequencies
- Sine .... 43 MHz
- Square .... 25 MHz
- Triangle, Ramp Up, Ramp Down, Noise .... 5 MHz
- User Defined .... 43 MHz

Frequency Resolution .... 355 nHz
Phase Resolution .... 0.0055°

Analog Output

Amplitude Range (Full Scale)
- Main Output Path .... 12 Vpp to 5.64 mVpp (50 Ω load)
- Direct Path .... 1 Vpp to 0.707 Vpp (50 Ω load)

Offset Range .... ±25% of Amplitude Range
DC Accuracy .... ± 0.4% of Amplitude ± 0.05% of Offset ± 1 mV
AC Amplitude Accuracy .... ± 1.0% of Amplitude ± 1 mV at 50 kHz
Output Filters .... Software selectable seven-pole elliptical analog filter and finite impulse response DAC digital interpolating filter
Passband Flatness .... +0.6 dB to -0.4 dB (100 Hz to 40 MHz) for Direct Path

Spectral Characteristics

	Frequency	Direct Path	Low Gain Path
Signal to Noise and Distortion (SINAD)	1 MHz	64 dB	66 dB
	10 MHz	61 dB	60 dB
Spurious Free Dynamic Range w/ Harmonics	1 MHz	-76 dBc	-71 dBc
	10 MHz	-68 dBc	-64 dBc
Spurious Free Dynamic Range w/o Harmonics	1 MHz	-88 dBFS	-91 dBFS
	10 MHz	-87 dBFS	-89 dBFS

Amplitude –1 dBFS Measured from DC to 50 MHz

Average Noise Density

	Amplitude Range		Average Noise Density		
Path	Vpk-pk	dBm	nV / √Hz	dBm/Hz	dBFS/Hz
Direct	1	4.0	18	-142	-146.0
Low Gain	0.1	-16.0	9	-148	-132.0

Sample Clock

Sources .... Internal Divide-by-N, Internal High-Resolution, External CLK IN, External DDC Clk In, PXI Star Trigger, PXI_TRIG <0:7>
Frequency Resolution
- Divide-by-N .... (100 MS/s) / N where 1 ≤ N ≤ 4,194,304
- High Resolution .... 1.06 µHz

System Phase Noise and Jitter[1]

	System Phase Noise Density	System Output Jitter
Divide-by-N	-137 dBc/Hz (10 kHz offset)	< 1.0 ps rms
High Resolution	-126 dBc/Hz (10 kHz offset)	< 4.0 ps rms

[1]10 MHz carrier

Onboard Clock (Internal VCXO)

Clock Source .... Phase locked to reference clock or derived from onboard VCXO frequency reference.
Frequency Accuracy .... ±25 ppm
PLL Reference Sources .... PXI_CLK10, CLK IN

Digital Data and Control, DDC

Data Output Signals .... 16 LVDS data lines (ANSI/TIA/EIA-644 compliant)

Start Trigger

Sources .... PFI <0:3>, PXI_TRIG<0:7>, PXI Star Trigger, Software, Immediate
Modes .... Single, Continuous, Stepped, Burst

Markers

Destinations .... PFI <0:1>, PFI <4:5>, PXI_TRIG <0:7>
Quantity .... 1 Marker per Segment

Waveform and Instruction Memory Utilization

	32 MB Standard	256 MB Option	512 MB Option
Onboard Memory Size	33,554,432 bytes	268,435,456 bytes	536,870,912 bytes

Loop Count .... 1 to 16,777,215. Burst Trigger: Unlimited

Memory Limits

	32 MB Option[1]	256 MB Option[1]	512 MB Option[1]
Arbitrary Waveform Mode Maximum Waveform Memory	16,777,088 Samples	134,217,600 Samples	268,435,328 Samples
Arbitrary Sequence Mode Maximum Waveform Memory[2]	16,777,008 Samples	134,217,520 Samples	268,435,200 Samples
Arbitrary Sequence Mode Maximum Waveforms[3]	262,000	2,097,000	4,194,000
Arbitrary Sequence Mode Maximum Segments in a Sequence[4]	418,000	3,354,000	6,708,000

[1]Refer to detailed specifications for all trigger modes. [2]Condition: One or two segments in a sequence.
[3]Condition: One or two segments in a sequence. [4]Condition: Waveform memory is <4,000 samples.

Maximum Waveform Playtimes

	32 MB Option	256 MB Option	512 MB Option
100 MS/s sample rate, OSP disabled	0.16 s	1.34 s	2.68 s
1 MS/s IQ rate, real mode, OSP enabled	16 s	2 min 14 s	4 min 28 s
100 kS/s IQ rate, real mode, OSP enabled	2 min 47 s	22 min 22 s	44 min 43 s

[1]Single trigger mode. Playtimes may be extended using waveform linking and looping.

Power[1]

+3.3 VDC	+5 VDC	+12 VDC	-12 VDC	Total Power
1.9 A	2.2 A	0.46 A	0.01 A	22.9 W

[1]Typical

Environment

- Operating Temperature .... 0 ºC to +55 ºC (Meets IEC-60068-2-1 and IEC-60068-2-2)
- Storage Temperature .... -25 ºC to +85 ºC (Meets IEC-60068-2-1 and IEC-60068-2-2)
- Operating Relative Humidity .... 10% to 90%, non-condensing (Meets IEC 60068-2-56)

Calibration

Self-Calibration .... DC gain and offset
External Calibration Interval .... 2 years

Certifications and Compliances CE

CE Mark Compliance

Note

Unless otherwise noted, the following conditions were used for each specification:

A. Analog Filter enabled.
B. DAC Interpolation set to maximum allowed factor for a given sample rate
C. Signals terminated with 50Ω.
D. Direct path set to 1 Vpk-pk, Low Gain Amplifier Path set to 2 Vpk-pk, and High Gain Amplifier Path set to 12 Vpk-pk.
E. Sample clock set to 100 MS/s

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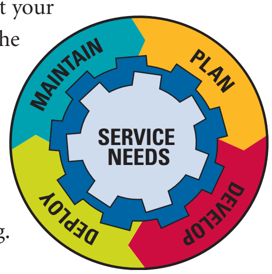

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NI training is the fastest, most certain route to productivity with our products. NI training can shorten your learning curve, save development time, and reduce maintenance costs over the application life cycle. We schedule instructor-led courses in cities worldwide, or we can hold a course at your facility. We also offer a professional certification program that identifies individuals who have high levels of skill and knowledge on using NI products. Visit **ni.com/training**.

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Hardware Services

NI Factory Installation Services

NI Factory Installation Services (FIS) is the fastest and easiest way to use your PXI or PXI/SCXI combination systems right out of the box. Trained NI technicians install the software and hardware and configure the system to your specifications. NI extends the standard warranty by one year on hardware components (controllers, chassis, modules) purchased with FIS. To use FIS, simply configure your system online with **ni.com/pxiadvisor**.

Calibration Services

NI recognizes the need to maintain properly calibrated devices for high-accuracy measurements. We provide manual calibration procedures, services to recalibrate your products, and automated calibration software specifically designed for use by metrology laboratories. Visit **ni.com/calibration**.

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