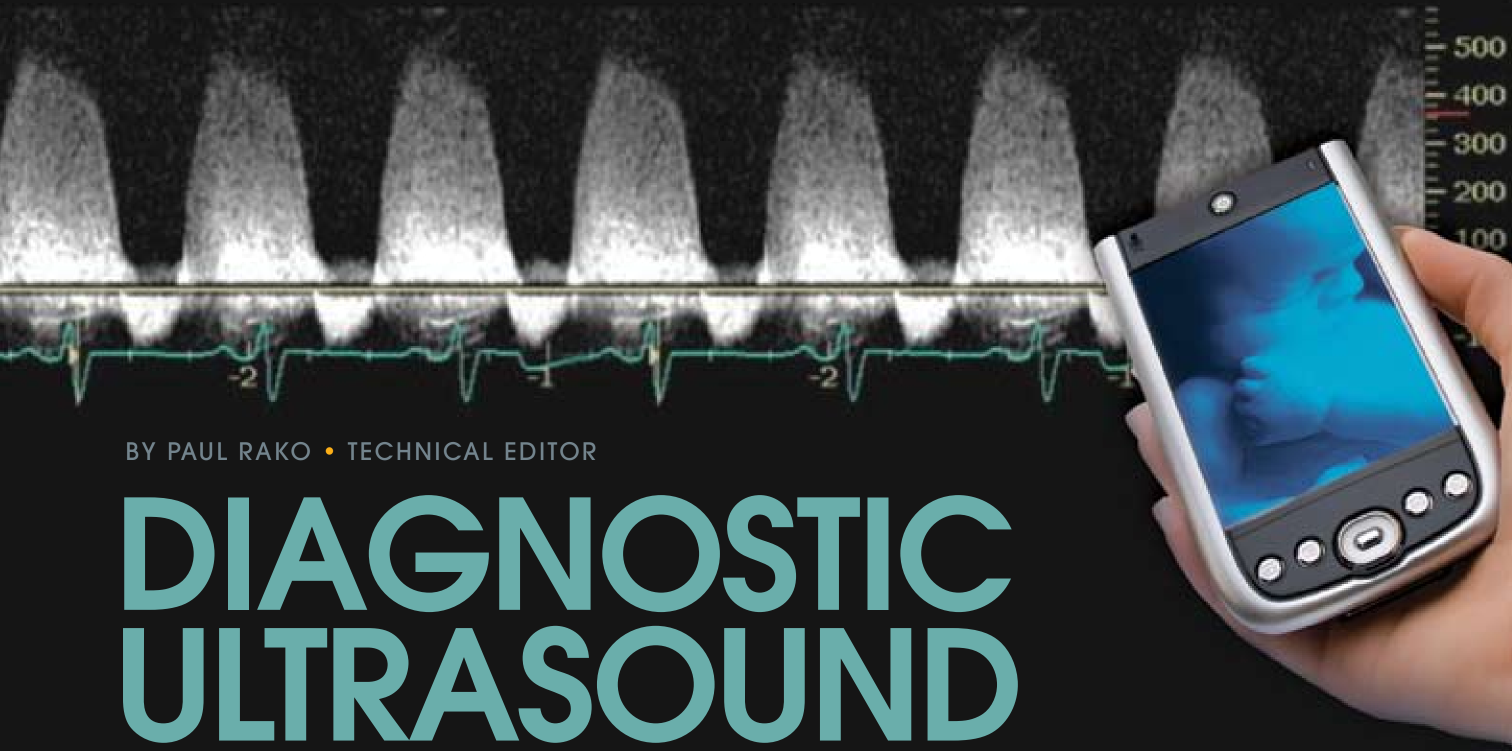


This output of a CW-Doppler system (above left) does not show an image of your body. It represents blood flow over time. You can measure maximum velocity and observe the negative periods of blood flow as arterial valves close. A cardiogram signal is superimposed below the ultrasound signal (courtesy Analog Devices).
By using a 2-D transducer array (above right) or wobbling a linear array with a stepper motor, you can derive a 3-D ultrasonic image (courtesy Texas Instruments).

BY PAUL RAKO • TECHNICAL EDITOR

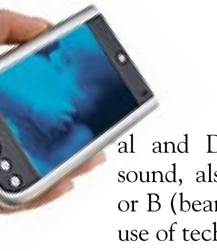
DIAGNOSTIC ULTRASOUND GETS SMALLER, FASTER, AND MORE USEFUL

THE SIGNAL PATH IN ULTRASOUND MACHINES IS A MULTICHANNEL TRANSMITTER-RECEIVER SYSTEM WITH BLAZINGLY FAST DATA RATES. ENGINEERS NEED TO WEIGH A HOST OF OPTIONS IN DESIGNING THESE COMPLEX MACHINES.

Developers of diagnostic-ultrasound machines must carefully consider these devices' design and their intended applications, making trade-offs among such factors as SNR (signal-to-noise ratio), channel count, selection of ADCs, Doppler versus conventional technology, PW (pulsed-wave) versus CW (continuous-wave) approaches, power consumption, cable selection, and cost. With advancements in electronics, smaller and faster machines are emerging that are applicable in a variety of new applications. Portable and 3- and 4-D machines are also making inroads in this expanding field.

The diagnostic-ultrasound technique creates images of organs and measures blood flow within patients' bodies (**Figure 1**). The technology is now also finding use in therapeutic applications, such as targeted drug delivery. In this scenario, the machine emits a pulse waveform that couples with microspheres in a patient's blood; the pulses break these spheres, accurately delivering drugs to their intended targets. Other applications include chemopotentiation, which helps chemotherapy drugs find and destroy cancerous tumors, and veterinary medicine, in which patients cannot verbally describe symptoms.

You can divide diagnostic ultrasound into two broad categories: convention-



AT A GLANCE

- Physicians use ultrasound therapeutically for tasks such as breaking up kidney stones and diagnostically for peering into patients' bodies.
- You can divide diagnostic ultrasound into conventional B (body)-wave, PW (pulsed-wave) Doppler, and CW (continuous-wave) Doppler.
- The transmitting path applies digital pulses or DACs to high-voltage amplifiers.
- The receiving signal path is similar to that of a phased-array radar system.
- Spatial resolution is a function of the channel count and the SNR (signal-to-noise ratio) of the signal path.

al and Doppler. Conventional ultrasound, also known as B (body) mode or B (beam) scan, represents the classic use of technology: to peer into organs of the body, perhaps to determine the sex of a fetus. Doppler ultrasound relies on the Doppler effect, which takes its name from Austrian mathematician Christian Doppler, who proposed it in 1842. The Doppler effect describes the change in the frequency of sound waves for an observer relative to the source of the waves. You can imagine this effect when you think of the sound an ambulance siren makes as it approaches you, when it is right next to you, and as it moves away from you. PW, or color, Doppler encodes velocity information as colors on a display. CW, or spectral, Doppler broadcasts a continuous wave of sound into the body and measures the phase shift of the returning signals. This technique yields only velocity information, with no profile of where the velocities occur.

All ultrasound systems are able to use beam-forming and beam-steering approaches—signal-processing techniques for directional-signal transmission or reception. Physicians can employ PW-Doppler technology to map a patient's interior organs and blood flow, for example. CW systems must be aimed at a certain point because they have no way of knowing where the blood is flowing. For this reason, physicians typically use CW Doppler as an add-on to a conventional ultrasound-signal path. The physician can find an artery or a vein with conventional ultrasound and then closely examine its blood flow with the high resolution of CW techniques.

Doppler systems employing beam-steering use linear arrays of piezoelectric transducers that steer the beams and provide for increased spatial resolution. By delaying the pulses on the center of a linear array, they can focus the transmitting pulse on one point in the body (**Reference 1**). Applying delay to the receiving side makes the reflected waves adhere to that point.

Figure 1 Portable ultrasound machines allow doctors to get early information about trauma and emergency conditions. US Army medics donated this SonoSite machine to the Hawija Hospital in Iraq. Major Charles Buck of the 25th Infantry Division shows an Iraqi physician how to use the machine (courtesy Sergeant Sean Kimmons, US Army).

Ultrasound machines can have 16 to 512 channels; those with fewer channels may be portable, whereas you may need wheeled carts to move larger machines with many channels. Having many signal channels affects not only the cost and size but also the power consumption of these machines.

Beware of manufacturers' channel-count claims, however, because they confuse some would-be purchasers. Some manufacturers use signal-processing techniques to increase the apparent channel count and then claim double the number of analog channels in the front end. Others multiplex the analog channels across a wider-channel-count transducer. For example, they may switch a 16-channel-wide analog-input section across a 64-channel transducer, perhaps moving one element at a time to "paint" an entire beam-formed area across the transducer length. Some manufacturers also provide more transmitters than receivers, an approach that can provide acceptable but less accurate results than using one analog channel for each transducer element. To increase spatial resolution, you can use more analog channels than elements and focus between elements, according to Lee D Dunbar, vice president of market innovation at SonoSite, a maker of portable ultrasound equipment.

A recent development in this market is 3-D ultrasound, in which the transducer is a 2-D, rather than a linear, array. This approach allows the system software to create a 3-D view into a patient's body. (For more on 3-D ultrasound, see "Peering into ultrasound machines," *EDN*, this issue, pg 18.) A 4-D ultrasound adds a time dimension to a 3-D image. It can show a moving image of organs and structures inside the body.

Ultrasound images also rely on the SNR of the analog-signal path. If there is less dynamic range in the signal chain, the ultrasound system cannot discriminate among the reflected signals. The analog chips' high noise floor would mean that conventional ultrasound could not peer as far into the body and would not resolve small features, whereas CW-Doppler ultrasound would not pick up slow or subtle variations in blood flow. By trading off channel count versus SNR, however, designers can provide the system software with enough information to make accurate images.

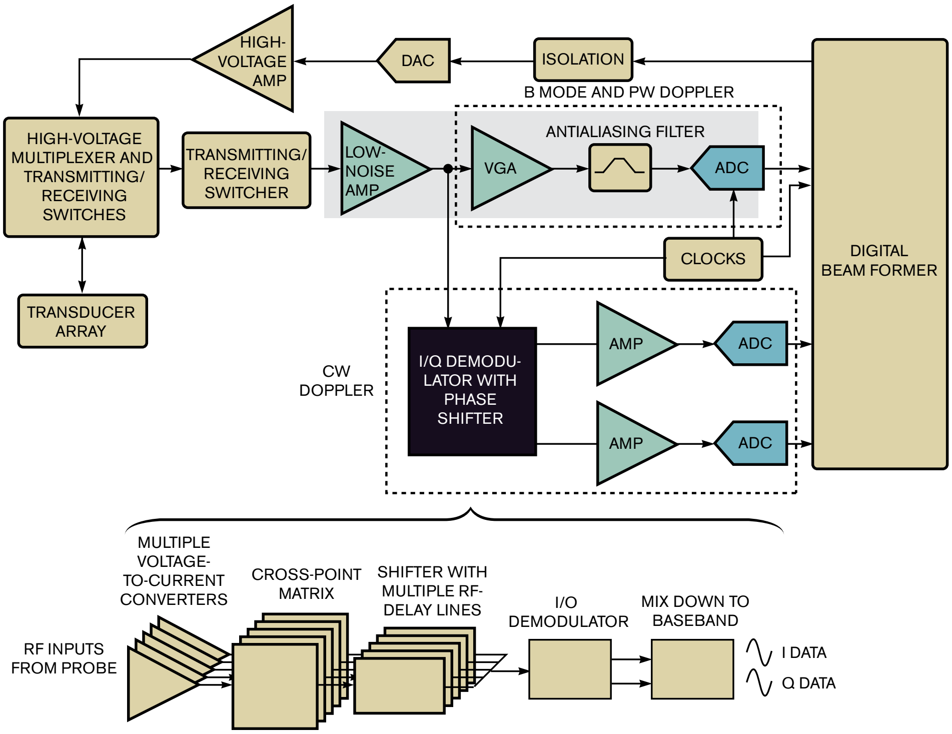


Figure 2 The analog front end of an ultrasound machine is a complex transmitter-receiver system similar to those of phased-array radar systems (courtesy Analog Devices).

As in most analog-signal paths, the first amplifier in the receiver path controls SNR. You can increase SNR by broadcasting a larger pulse into the body, but you must stay within the safe limits of energy. The ADC in ultrasound systems must provide enough SNR to accommodate the amplifier chain in front of it. In modern systems, this task requires a 12-bit ADC for the pulsed path and at least an 18-bit unit for the CW path. Similarly, you can increase SNR in an analog-signal chain by burning more power in the front-end amplifiers, but this approach affects battery-power consumption. Equally daunting, if you build a system with hundreds of channels, you need the digital processing and software to do something with all the information. This approach also consumes power. You can use a "slice-count" technique—that is, increase the number of channels—to improve not only the resolution but also the speed of imaging and the volume of tissue you can examine.

A medical-ultrasound-signal path looks similar to that of a phased-array radar installation, except that the ultrasound-signal path operates at much lower excitation frequencies. Unlike a radar receiver, a modern ultrasound unit may be a portable device that fits into the palm of your hand and runs on batteries. These machines transmit a 2- to 17-MHz ultrasound frequency into a patient's body; the lower the frequency, the deeper the machine can peer into the body. The round-trip attenuation of an ultrasonic signal in the body is 1.4 dB/cm-MHz. Doppler systems can discriminate the velocity of only those particles that are smaller than the wavelength of the excitation frequency. Ultrasound cannot travel through air, so physicians typically apply a gel to the skin where they are using the transducer. Specialized transducers work inside the body to provide closer examination of the esophageal, reproductive, or digestive tracts. The ultrasound signal does not penetrate air-filled cavities in the body, including lungs and intestines; it can transmit images only from organs and from measuring blood flow.

A medical-ultrasound system is in many ways similar to other communication systems (**Figure 2**). The presence of multiple transmitters and receivers gives ultrasound a similarity to MIMO (multiple-input/multiple-output) wireless systems. The same ADC might find use in either system, according to Allan Evans, vice president of marketing for fabless-semiconductor company Samplify Systems. The transmitting section emits a pulse in the same way that a sonar or a radar system does. The input section is a receiver similar to a radar receiver, except that it works at the speed of sound instead of the speed of light. The input path of a CW-Doppler-ultrasound system has I (in-phase) and Q (quadrature) demodulation that is familiar to the designers of base stations and cellular phones.

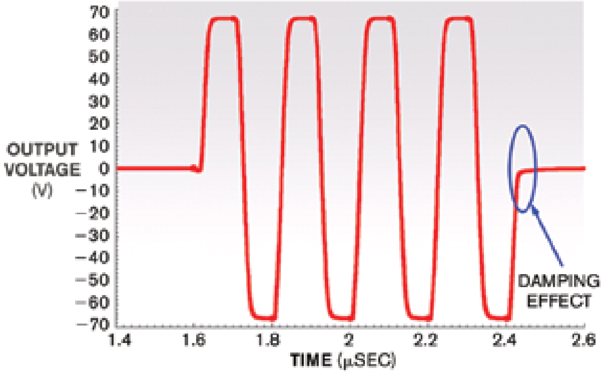


Figure 3 The transmitted pulse from an ultrasound system affects the quality of the image the software produces (courtesy Texas Instruments).

The transducers usually comprise quartz-piezoelectric materials. Researchers are also developing MEMS (microelectromechanical-system) CMUTs (capacitive-micromachined-ultrasonic transducers) to create and receive the sound pulses. One advantage of these devices is that they can make repetitive linear and 2-D arrays. "These CMUTs [eliminate] the whole interconnect problem," says

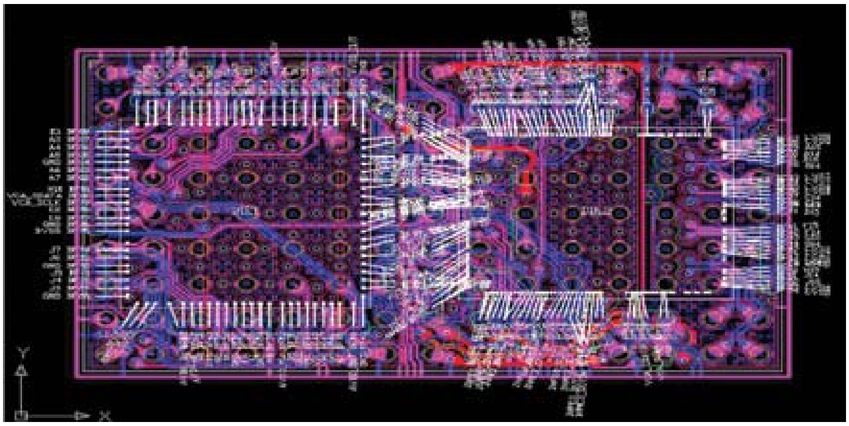


Figure 4 Rather than make the analog front end on one die, Texas Instruments combines a silicon-germanium die and a CMOS die into one package.

John Scampini, director of strategic marketing at Maxim Integrated Products. In addition, designers can include some circuitry on the transducer itself because it is a silicon die. Unfortunately, these devices are currently in the research phase.

In general, most ultrasound machines have no signal-processing abilities in their transducer heads. Instead, all of the channels connect through coaxial cables that must withstand 150V transmitting pulses and must have low stray capacitance to carry the received signals without undue attenuation. Gore, a participant in the ultrasound-imaging-equipment area and a range of other consumer and electronics markets, makes a ribbon-based cable that is electrically equivalent to but thinner than 75Ω coaxial cable. This thinner cable targets use in sonographic ultrasound whose operators experience repetitive-stress injuries from manipulating heavy cables. Gore's thinner and more flexible cables solve this problem for the operators of these machines. Also, machines that create virtual channels by multiplexing 16 analog channels across a 64-element transducer may include multiplexing circuitry in their transducer heads—a benefit because the cable needs to carry only 16 analog channels and can be four times thinner and one-fourth the cost of a 64-channel cable.

Ultrasound transmitting side of an ultrasound system needs to deliver high-voltage pulses to the transducer elements. The ultrasound machine delays the pulses at the center of the linear transducer so that the sound waves converge on a point inside the body. For this reason, each channel needs its own pulser and perhaps a DAC. The voltages are typically 70V or higher, and peak output currents reach ±2A. Frequencies range from 2 to 17 MHz, and burst times are 1 μsec to several microseconds. The waveshapes are often just simple digital pulses, but more advanced machines include DACs to tailor the pulse shapes. In this case, the transmitter-driver chip is not a simple MOSFET array but a high-voltage amplifier. These DAC-generated pulses can be useful in therapeutics, in ultrasounds using contrast agents, and in chemopotentiation. The quality of the burst waveshape also factors into the image quality. Texas Instruments, for example, ensures that its TX734 pulser transmitter has no undue ringing as the burst ends (**Figure 3**). In CW-Doppler applications, you use one-half of the transducer array as transmitters and the other half as receivers.

The receiver side of a medical-ultrasound system shares many characteristics of communications receivers. Because a 150V transmitting pulse would overload any amplifier system, the first block is a switch that protects the amplifiers from the transmitting pulse and then quickly switches in the transducer so that it can receive the sonic echoes. These switches are distinct from systems that may be multiplexing 16 analog channels into a 64-element transducer. All ultrasound systems need the receiver switches to prevent overloading in the signal path. The switches are often current-fed diode bridges, much like the front end of a sampling oscilloscope (**Reference 2**).

The first gain block is a fixed-gain, low-noise amplifier that typically runs at 19 dB and often has an active-termination network to minimize noise. The amplifier's noise limits the SNR of the entire signal path. In addition, the amplifier must have a sufficient power supply so that there is no clipping of the signal. Input signals can be 0.5V p-p from hard reflections, such as the bone in the patient's body that is closest to the transducer. Furthermore, should the inputs overload, the low-noise amp must quickly and predictably exit saturation.

Figure 5 Ultrasound systems are becoming available in handheld form factors (courtesy Signostics Medical).

Manufacturers frequently use a silicon-germanium or a CMOS process for low-noise amps, but silicon germanium provides better linearity and a lower noise figure (**Reference 3**). You can operate amplifiers employing this process at a higher supply voltage, ensuring that you do not overload the amplifier. Another benefit of silicon germanium is that it yields a low flicker-noise corner, an important criterion in CW-Doppler ultrasound. Even though the flicker noise is worse at dc, it still modulates the signal when it passes through the I- and Q-demodulator sections. Thus, the flicker noise results in a broader "skirt," the widening of the base of the frequency-domain-receiver spectrum. This phase noise obliterates small Doppler signals and prevents the display of slow and subtle changes in blood flow.

On the other hand, using large CMOS transistors reduces voltage noise. Analog Devices, for example, claims that its AD9272 low-noise amplifier has lower terminated noise than any other analog front end. CMOS always excels at current-noise specifications because the input-bias currents are so low to begin with. "CMOS has the advantage of having very low input-noise current," says Corey Peterson, project leader of the AD927x-product line at Analog Devices. "For higher probe impedance, the input-noise current can be as significant as the input-noise voltage." He also notes that the company's triple-well process prevents digital-substrate currents from interfering with the analog signals and that using large input transistors can reduce flicker noise to acceptable levels. Although the higher flicker-noise corner of CMOS is unavoidable, it is often acceptable if you do not use CW mode and if the machine is a low-performance portable model.

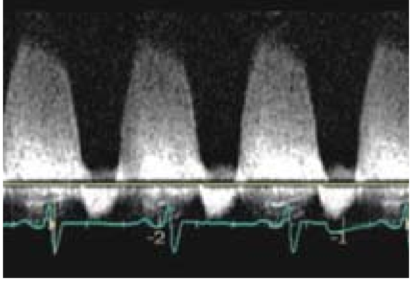
After passing through the low-noise amplifier, the signal splits off between a CW-Doppler path and a B-mode path and conventional color-Doppler path. The conventional path starts with a PGA (programmable-gain amplifier) that typically adds 40 dB of gain. The PGA varies dynamically as it receives each pulse; thus, the signals that reflect from deeper in the body receive more gain. This approach allows a channel SNR of 110 dB and extends the effective 70-dB dynamic range of a 12-bit ADC. As with a low-noise amp, bandwidths for PGAs are approximately 20 MHz. One vital characteristic of PGAs is recovery from overload. You can expect hard tissue or bone to reflect a large signal that overloads the PGA. The system can sense this signal and reduce the gain at that point in the receiving time, but the faster the PGA recovers from overload, the sooner the system will have accurate information to process. Overload can also create frequency modulations that are indistinguishable from blood flow in a Doppler system.

Amplifier and ADC vendors measure overload recovery differently, and even ADC vendors differ among themselves in how they evaluate overload recovery. This measurement is not so much about specmanship but about the probabilistic nature of the overload regimens the system must undergo. "You have to work with customers carefully and closely to translate what is a system phenomenon of overload into a spec for a part," says Scott Pavlik, a marketing manager in the health-care segment at Analog Devices.

An antialiasing SAW (surface-acoustic-wave) or a passive filter follows the PGA. Although the 20-MHz bandwidth is high for active filters, amplifiers are continuously pushing this boundary. It is common for the ultrasound ADC to operate at 50M samples/sec so that the antialiasing filters have sufficient roll-off and flatness to prevent higher-frequency harmonics from mixing back into the signal and reducing quality. With active filtration, however, you also must speed up overload recovery. Passive networks, on the other hand, need no recovery period. You should characterize your SAW devices for overload, but they also recover nearly instantaneously.

The analog signal ends at the ADC, which is typically a 12-bit, 50M-sample/sec pipeline device. Older systems use 8-bit converters for B-mode scans, but the requirements of pulsed Doppler have driven bit counts to 12. Another factor to consider is harmonic-imaging mode. Compressed tissue under an ultrasound pulse reflects back second harmonics, and a 12-bit converter allows you to sense these harmonics and compensate for the tissue compression, allowing for better resolution in the scan. Although SAR (successive-approximation-register) converters provide better SNR figures, pipelined converters are acceptable. The VGA rather than the ADC determines the SNR of the signal chain. How quickly the converter recovers from overload conditions may be more important than SNR, however.

DOZENS OF CHANNELS OF 12-BIT DATA WOULD USE UP ALL OF THE PINS ON EVEN THE LARGEST FPGA.

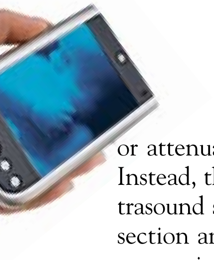


Ultrasound systems can alternatively use CTSD (continuous-time-sigma-delta) converters, which are available from National Semiconductor and Analog Devices. Systems using this topology have low power consumption for their speed and SNR. CTSD converters also require no antialiasing filter in front of the converter because the loop filters in the converters inherently prevent aliasing. With CTSD converters, the internal loop amplifiers control the bandwidth, so you cannot undersample them. As a result, a 50M-sample/sec CTSD converter can operate only at that sampling rate; it doesn't work at 25M or even 40M samples/sec. Another caveat has to do with overload recovery. Because pipelined converters carry their samples in separate sections of a pipeline, they inherently recover well from overload—often during one sample. CTSD-ADC designers must tack overload recovery with clamping networks onto the internal integrator, an approach that typically reduces SNR and increases power consumption while the part is in an overloaded state. This situation is not a serious problem because the ADC typically does not remain in saturation for more than a few cycles.

Because dozens of channels of 12-bit data would use up all of the pins on even the largest FPGA, the converters use serial outputs, such as LVDS (low-voltage-differential signaling). Parts that have eight ADC channels in one package and multiple channels on one pair of differential outputs further reduce the pin count in beam-former FPGAs. Be aware that SNR specs can be deceiving. "An ADC can have very poor near-carrier SNR and still having excellent full-Nyquist-band SNR specifications," says Maxim's Scampini, who also warns that flicker noise in the ADC reference can cause poor near-carrier SNR.

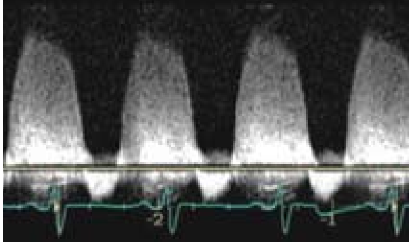
The other analog path in a medical ultrasound front end is for CW Doppler. This path needs greater SNR than the 110 dB that the B-mode and PW-Doppler paths provide. "Bear in mind that the transmission signal is continuous and is also being received," says Samplify's Evans. "You can also imagine that the refection from a blood vessel wall would be far larger than the Doppler scattering of the blood carried inside the vein. In the CW Doppler, you are trying to maintain a dynamic range of 154 dBm [decibels referenced to milliwatts]/Hz. The thermal noise floor of 50Ω is −174 dBm/Hz."

Because the CW-Doppler technique does not use pulses, you cannot disregard the large signals by blanking them out



or attenuating them for a certain time. Instead, the technology picks off the ultrasound signal after the low-noise-amp section and sends them to a demodulator section that performs analog-signal processing. Doppler signals represent changes in phase, so the I and Q demodulation that advanced-communications techniques use is also applicable to mixing down the 2-MHz CW signal to baseband. This demodulation allows the system to discriminate between blood flow toward the sensor and blood flow away from the sensor. The I and Q components then go to a higher-resolution, slower-sampling ADC. Demodulation has moved down the signal from the frequency of the transmitting pulse to the frequency of blood flow in your veins. Suitable ADCs are 16- or 18-bit devices sampling at 150k or 100k samples/sec, respectively. The I and Q components then move to the spectral-processing subsection in the beam-former FPGA.

A FUNDAMENTAL CHOICE IN BUILDING AN ULTRASOUND SYSTEM IS HOW MUCH INTEGRATION TO USE.



INTEGRATION TRADE-OFFS

A fundamental choice you will have to make in building an ultrasound system is how much integration to use. Analog Devices this year won an *EDN* Innovation Award for its latest ultrasound front end (**Reference 4**). The company's eight-channel AD9276 includes the low-noise amp, the PGA, antialiasing filters, and an ADC—all on one CMOS-silicon die. Leveraging Analog Devices' expertise in communications, the part also integrates the I and Q demodulators. To make an analog front end, you would need to add only the transmitting functions, the input switches, and the amplifiers and ADCs for the CW-Doppler function. Texas Instruments' AFE5804 analog front end integrates the amplifiers and ADC in one package but uses a low-noise amp and VGA on a silicon-germanium process and mounts it as a separate die into the same package as the CMOS ADC (**Figure 4**). The company also offers the AFE5851, which integrates the VGA and ADC but omits the low-noise amplifier, so you can use an external part.

"Customers want in the long term to put the electronics into the transducer," says Veronica Marques, strategic-marketing manager for the medical-business unit at Texas Instruments. "If customers want to integrate the low-noise amp into the transducer, they can still use a TI integrated analog front end," she says. Choosing the integrated front end locks you into one vendor, making it impossible to upgrade separate blocks, such as the PGA or the VGA.

Maxim, on the other hand, offers high-performance, silicon-germanium, low-noise amps and then lets you choose PGAs and ADCs from the company or from a competitor. The MAX2038 integrates an amplifier with the quadrature mixer. The MAX2078 integrates the amplifier, VGA, filters, and CW-Doppler mixers across eight channels. If you want to differentiate your product by its software or user interface, using an integrated analog front end makes sense, especially if your design has space and power constraints. SonoSite, on the other hand, uses a proprietary analog front end because the results of the cost and design time show up in the displayed images. All of the company's analog front ends are custom-designed. "The chip makers are interested in leveraging our technologies," says the company's Dunbar. "But they still have a way to go."

Another integration factor involves the digital-data side of the front end. Samplify Systems, for example, which also this year won an *EDN* Innovation Award, does not integrate the low-noise amp and PGA into the ADC converter because high-voltage or low-noise processes are better suited to those blocks (**Reference 5**). Samplify's Evans notes that a low-power, 12-bit, 50M-sample/sec converter will work across several products—from cart-carried systems to portables. "You can then mix and match low-noise-amp/VGA front ends, depending on your power/performance trade-offs," he says. Samplify's 16-channel ADCs have built-in lossless and lossy data compression, reducing the cost, the complexity, and the data rates to the beam-forming chip. The reduced data rates have lower EMI (electromagnetic interference), and the compression routines also reduce frequency peaks and keep the EMI spectrum more like pink noise. In addition to the chips, the company can provide you the IP (intellectual property) for your FPGA or DSP to decompress the signal. One interesting development has been the use of lossy compression, which provides medical images that are indistinguishable from those from non-compressed systems.

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Other factors you should consider when using integrated chips are their availability and their obsolescence. Due to the fine-line CMOS content in a multichannel ADC system, many of the analog-semiconductor vendors farm the fabrication out to TSMC (Taiwan Semiconductor Manufacturing Co), UMC (United Microelectronics Corp), or other large digital-CMOS-fab vendors. This approach reduces your chances of ending up on an allocation list when the boom in semiconductor demand inevitably comes. Equally concerning is obsolescence. It is not beneficial to design in a proprietary chip for

cost, space, and power considerations if the vendor plans to stop producing the chip. Semiconductor vendors know that the medical-device market differs from the consumer-electronics market. Customers for medical devices must get FDA (Food and Drug Administration) approvals and expect chip runtimes of a decade or more. Although it is more difficult to win a medical-ultrasound socket, once a company gets that socket, the part can flourish for years. Even in a recession, people still become sick. Therefore, all the analog-semiconductor companies keep their proprietary chips in production for as long as customers need them.

Remember that the architecture of an ultrasound system involves an analog trade-off (**Figure 5**). You must decide whether CW-Doppler capability is important, given that it requires so many dedicated analog circuits. You must weigh multiplexing 16 channels into 64 against the performance this approach will yield. You must trade off silicon germanium versus CMOS, quartz versus MEMS, and DSPs versus FPGAs. Design cycles have decreased from five years to less than two years. A product that finds use in aircraft in a battlefield will need approvals from the FDA, Federal Communications Commission, CE (Conformité Européenne), FAA (Federal Aviation Administration), and Department of Defense. You may have to design systems that work in a decompression chamber to evaluate Navy SEAL (sea/air/land) special forces or Air Force personnel at altitudes of 30,000 feet.

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You can understand why engineers devote their entire careers to designing analog front ends for medical-ultrasound systems. "There are a lot of people that get into it and then get addicted to it," says SonoSite's Dunbar. "All of us are addicted to ultrasound. You are building something that helps somebody."**EDN**

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