# A Practical, High Performance Ultra-Wideband Radar Platform

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***Abstract*—This paper describes an Ultra-Wideband (UWB) chipset and platform that enables low cost implementation of high performance mono-static, bi-static and multi-static UWB radars. Key factors in the silicon implementation and system design are discussed as are several applications demonstrated to date.**

## I. INTRODUCTION

In 2002, the Federal Communications Commission (FCC) issued new rules that defined how Ultra-Wideband (UWB) transmissions would be permitted [1]. Somewhat later the National Telecommunications and Information Agency published rules for federal users [2]. Prior to this, the technology had been under development for at least two decades. At the time, it was thought that the effective legalization of the technology would result in a flood of new products. While a few UWB communications chipsets/ products are available and some UWB ranging/RFID products have been demonstrated and marketed, there have been very few demonstrations of low cost radar products. In short, the predicted flood of products has been slow in coming. This has been particularly disappointing as UWB radars offer more than a GHz of RF bandwidth and thus offer the resolution required to operate in high clutter environments.

One limiting factor in the development of UWB products has been the absence of a cost effective, high performance UWB chipset and associated demonstration platform or OEM module specifically tailored for radars. This absence is in large part due to three factors. First, it is very difficult to demonstrate high performance UWB radars without a chipset. Implementations based on the use of discrete components tend to be expensive, complex, likely to lack performance and are generally not credible. Second, a chipset is very expensive to develop. Without producing a high performance chipset, there will be little hope of demonstrating either widespread utility or a path to low cost devices. Third, it is difficult to achieve useful performance at the allowed transmit power level.

To address this need, Time Domain has developed the P400 UWB chipset and has implemented this chipset in a low cost OEM platform that allows the demonstration of mono-static, bi-static and multi-static radars. This paper describes the key design issues and compromises that defined the design, discusses the chipset and the associated platform then concludes with a summary of its use in a variety of applications.

## II. DESIGN ISSUES AND COMPROMISES

Implementation of a UWB radar chipset requires evaluation of six main design issues. These are:

- Selection of the target UWB waveform
- Choosing between coherent and non-coherent operation
- Deciding whether to support just mono-static operation or extend the capability to include bi- and multi-static operation
- Selection of the target silicon process
- Generation of the radar response data
- Deciding whether to provide an optimum detection algorithm or simply provide raw radar response data

The following sections provide a discussion of each of these trade spaces and describe what capabilities were included in the final design.

### *A. UWB Waveform Selection*

The FFC rules allow operation in several frequency bands. While the rules describe in detail the constraints on power spectral density in the various bands, there are few constraints placed on waveform signaling structure. As long at the power spectral density is beneath the legal limits and special care is taken to avoid or limit interference to other bands of operation, most notably the security of life frequencies between 1 and 2 GHz, the designer is reasonably free to use whatever UWB waveform he sees fit. For example, one could launch a single high energy UWB pulse at a relatively low repetition rate. Alternatively one could launch a sequence of low energy UWB pulses at a very high rate. It would also be possible to produce a UWB waveform based on frequency modulation of a carrier. Other options are conceivable.

The UWB waveform implemented in the Time Domain chipset was selected with the goal of maximizing radar

This research was funded in part through contracts with DARPA, NAVY, ONR, ARMY and Air Force.

**Accepted for presentation at IEEE-AESS RadarCon 2012 (Atlanta, Georgia May 7-11, 2012)**

performance. Because the most valuable characteristics of UWB radars are bandwidth and a comparatively low center frequency, the waveform was selected such that it offers the maximum possible bandwidth at the lowest possible center frequency. The waveform (shown in Figure 1) is centered at 4.3 GHz, occupies more than 2 GHz of bandwidth and achieves an effective RF bandwidth of 1.4 GHz.

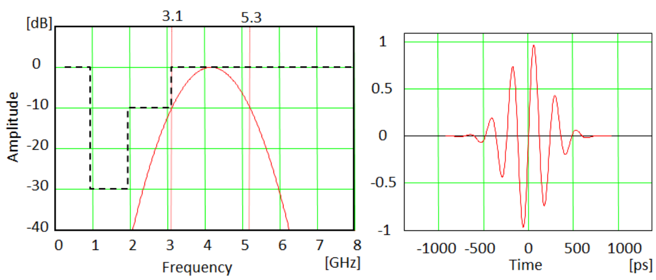


Figure 1. Transmitted waveform in frequency (a) and time domain (b).

This choice is important because maximizing bandwidth also maximizes resolution, thereby providing improved operation in high clutter environments. For applications that require operation through walls and concrete, a low center frequency offers the best propagation characteristics.

For implementation reasons and with a thought to maximizing the ability of a system to detect targets in close proximity to the antenna, it was decided to transmit individual pulses (as opposed to multiple smaller pulses) at a nominal pulse repetition rate of 10 MHz. (As a side note, rep rates from 1 to 20 MHz are supported.)

### *B. Coherent vs. Incoherent Operation*

One can design a radar for either coherent or incoherent operation. The key benefit of coherent operation is that it allows energy received from subsequent pulses to be summed. By integrating multiple returns it is possible to increase the signal SNR. Each doubling of integration increases SNR by 3dB. Since increasing the integration allows ever smaller signals to be detected, the dynamic range of the system is similarly increased.

Coherent operation comes at the cost of increased circuit complexity. In order to maintain coherence, the system timing must be held to a small fraction of the waveform's period, otherwise the signal will start to decorrelate and the benefits of integration will be lost. This requires that timing accuracy be held to better than 10 picoseconds. As will be discussed, this requirement is especially important for bi-static and multi-static radars. While difficult to accomplish, this level of performance can be achieved [3,4,5].

Since the FCC rules limit average transmit power to a miniscule 50 microWatts, it is necessary to use every trick possible, including coherent operation, to increase operating range.

### *C. Support for Mono-, Bi and Multi-static Operation*

While a mono-static radar offers considerable value, operation in bi-static or multi-static modes will increase overall performance. More specifically, a bi-static UWB radar will exhibit significant forward scatter gain as the target approaches the direct path. It has been our experience that this is so substantial, that propagation near the direct path is effectively closer to $1/r^2$. In any event, both factors extend operating range. Multi-static operation also increases coverage area while at the same time offering additional views of the target. These additional view angles increase the possibility of target characterization and/or classification.

However, in order to support bi- and multi-static operation, the transmitter and receiver must be synchronized. This is normally accomplished either by separating the antennas on a single unit or connecting separate transmitters and receivers with a common clock. In either case, the transmit and receive antennas are effectively connected with hardware.

This limitation has been overcome by designing the system such that the clock can be transmitted wirelessly. This is accomplished by embedding a code in the polarity of the transmitted pulses. Encoding allows the receiver to synchronize its clock with the received pulse train. Synchronization is accomplished using an acquisition algorithm reminiscent of those used in a cell phone receiver. Once again, maintaining coherence is critically important. If the clocks cannot be synchronized to better than 10 ps, then coherence and operating range will greatly degrade. In a worst case situation it may not be possible to close the link and the ability to operate as a bi- or multi-static radar will be lost.

Synchronization also requires implementation of a dual receiver configuration in which one receiver acquires and locks to the transmitted train of UWB pulses and the second receiver captures the radar pulse response. This technique was initially developed to measure the leading edge for Two Way Time of Flight UWB Ranging [6,7,8] but is essential for wireless bi-static radar operation. Extending operation from bi-static to multi-static operation is quite straightforward as one only needs to add additional receiving UWB platforms to the area of operations.

This capability comes at significant additional cost in that a dual receiver must be implemented and an acquisition process must be added. This cost also comes with an additional benefit. Once acquisition has been added, it is a relatively simple matter to add data to the transmissions. Doing so increases functionality by allowing a single UWB platform to operate both as a multi-mode radar and as a radio.

### *D. Target Silicon Process*

Because the allowable transmit power is quite limited, every effort was made to maximize the performance of the receiver. To that end, the UWB chip was implemented using IBMs Silicon Germanium (SiGe) process. This process offers exceptionally low 1/f noise making it superior to the various RF CMOS technologies.

### *E. Generation of radar response data*

UWB radars capture the radar pulse response in a different manner than conventional radars. Most radars will down convert the radar pulse response, split the video signal into an I and Q channel and then digitize the two baseband signals. In contrast, a UWB radar will digitize the signal directly from the output of the antenna LNA and use a Hibert transform to produce I and Q data streams. To simplify the requirements of the digitizer, the radar pulse response is measured using a technique analogous to the way in which a sampling scope measures waveforms. The receiver uses an analog to digital converter to measure the pulse response at a given time offset relative to pulse transmission. By measuring the radar response to a large number of pulses and using a step and repeat measurement process it is possible to capture the equivalent pulse response. Furthermore, this process can be repeated such that the response is coherently integrated. In any event, the time required to record the radar response is a function of the raw pulse rate, the step size, the duration of the range window, the amount of integration required and the number of analog-to-digital converters used in the receive rake architecture. While these parameters are largely programmable, the default settings (step size = 64ps, raw pulse rate = 10MHz, integration = 64:1 and range window = 5.8ns) will produce a radar response at the rate of 20 kHz. This rate is the system PRF or the rate at which the equivalent pulse response is reported. Furthermore, and at the risk of confusion with general radar usage, Time Domain refers to this captured radar response as a "scan" and the equivalent pulse repetition rate as the scan rate.

### *F. Optimum Detection Processing vs. Providing Waveform Scans*

Most radars are designed to address a particular application and generally provide as an output just the detection information. In order to address the largest number of applications possible, it was decided to provide the user with the ability to collect raw waveforms ("scans") such that it will be possible to tailor the signal processing to the target application. While the platform is provided with generic bandpass and motion filters as well as a detection engine, this generic processing is not expected to satisfy all needs.

## III. CHIPSET AND PLATFORM

The P400 UWB chipset is currently implemented as a pair of mixed signal SiGe ASICs and a Digital Baseband ASIC. The first SiGe ASICs is called the Pulser and is responsible for generating the transmit waveform. The second SiGe ASIC is called the Analog Front End (AFE) and contains all of the required timing and receive circuitry. This includes the following:

- A communications channel by which the baseband controls the transmit timer and dual receivers
- Timing generator that drives either the Pulser or the Acquisition/Lock receiver
- Timing generator for the rake receiver
- Low Noise Amplifiers
- High speed waveform samplers
- Analog to Digital Converters
- All I/O drivers for moving data to the Baseband.

A block diagram of the AFE is shown in Figure 2.

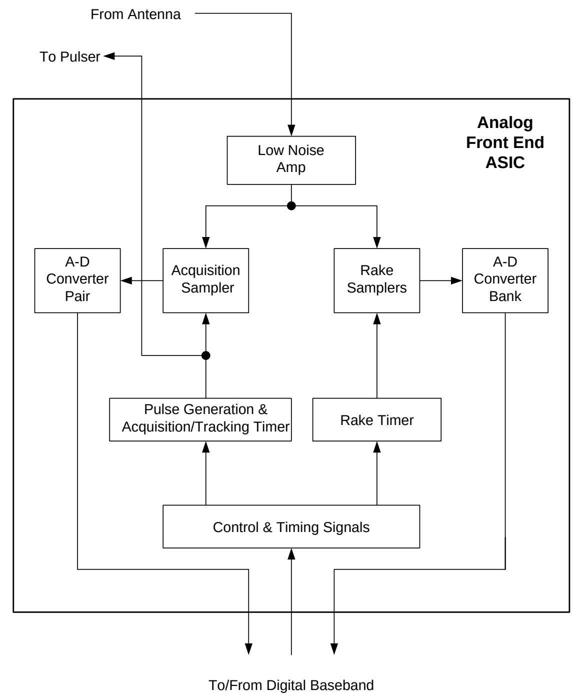


Figure 2. Block diagram of the Analog Front End ASIC.

The Digital Baseband has been implemented with a Xilinx Field Programmable Gate Array (FPGA). While Custom and Structured ASICs were considered, the dramatic increase in both FPGA performance and affordability made it the logical choice for small and mid-sized applications. Because the FPGA is reprogrammable, it also allows the addition of new features as well as refinement of existing capabilities. These devices have been incorporated into a standalone platform called the P400. A block diagram is shown in Figure 3.

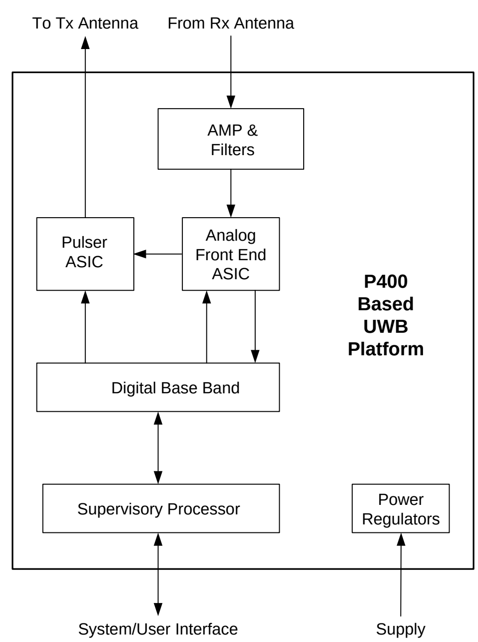


Figure 3. Block diagram of the P400 UWB platform.

As a side note, Time Domain expects to merge the two SiGe chips into a single device. Platforms based on this device are expected to be generally available in summer of 2013. By reducing all of the fundamental UWB circuits to two primary ASICS, one for mixed signals and one for the digital baseband function, and then limiting the balance of the hardware to a handful of discrete components, it is possible to greatly reduce the cost of the platform. In extremely large volumes, the cost of the hardware could be well below $100.

A photo of the P400 platform is provided in Figure 4.


Figure 4. Photograph of the P400 UWB platform (75mm x 100mm).

The P400 platform interfaces to either a personal computer or an embedded processor through either an Ethernet or Serial interface. Interface with the P400 is defined by an Application Programming Interface (API). This interface allows the user to configure the radar, control its operation, define radar scan parameters and collect radar scans. A Graphical User Interface (GUI) has been provided to illustrate the interface and demonstrate performance. The GUI also allows the user to view collected waveforms in real time and store them to disk. A graphic of the radar scan display page is provided in Figure 5. Note the user can receive and plot raw radar scans, bandpass filtered scans, motion filtered scans and/or detection data. All of this data can also be stored to log files. Doing so enables the developer to use MATLAB® and other analysis tools to evaluate radar performance and develop signal processing optimized for a specific application.

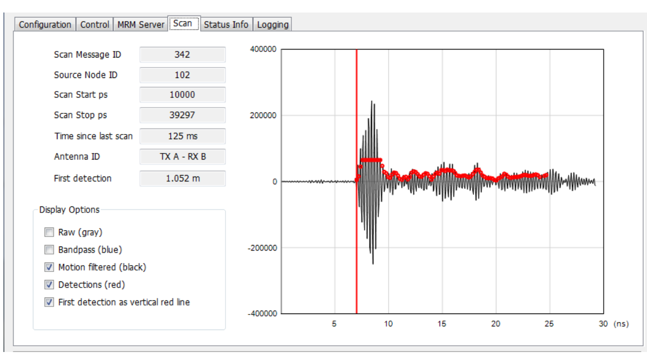


Figure 5. Example display of radar scan.

## IV. Example Applications

Time Domain UWB radars have been used in a variety of applications. Most of these applications are based on either mono-static or bi-static operation. Figure 6 shows data collected by P400 radars operated in mono-static and bi-static modes.

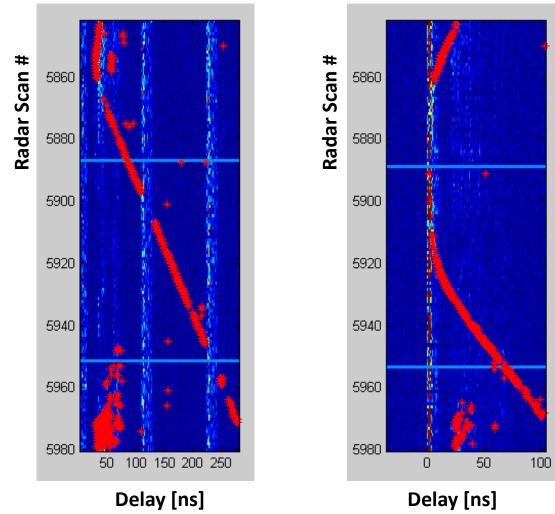


Figure 6. Waterfall plots of mono-static (left) and bi-static (right) radar returns with detection shown in red. Scans rate equal 4 Hz.

These waterfall plots show the radar returns as a person approaches and then retreats from the radar. The oldest radar scan is on top of the y-axis and youngest on the bottom. The y-scale is in increments of 0.25 seconds. The horizontal axis is in nanoseconds of delay. In the case of a mono-static radar, delay is measured relative to the start of transmission. For a bi-static or multi-static radar, delay is measured relative to beginning of the received waveform. The horizon lines at approximately 5885 and 5955 are associated with CFAR recalibration.

For the mono-static waterfall plot, one can readily detect targets at maximum range of at least 280 ns. This corresponds to a range of approximately 42 meters (140 ft.). The vertical stripe at 120 and 240 ns are artifacts associated with the pulse transmission repetition rate. This effect can be lessened by dynamically changing the repetition rate or by increasing the integration rate.

For the bi-static waterfall plot, one can readily see strong detections as the target approaches or recedes from the direct path between the transmitting and receiving radars. When the target is directly on the direct path, it may also intermittently block reception.

Multiple devices can be assembled to form a hybrid mono-static, bi-static and multi-static RF fence. Such a system can be used to track targets as they move through a perimeter. A recent example is shown in Figure 7.

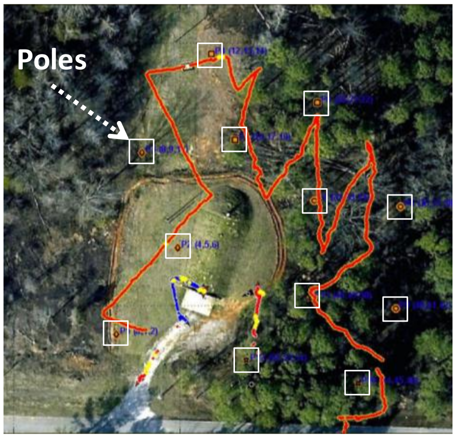


Figure 7. P400 radars (white square) used to track a target (red path) through a terrain (130m x 110m) of mixed forest and meadow.

This system also used the acquisition capability of the bi-static radar to establish a radio communications channel. Data is communicated by changing the polarity of the transmitted radar pulse (BPSK modulation). Once the signal had been demodulated, the polarity of the radar pulse was restored. The communications channel was used to form a Time Division Multiple Access network so that operation of the radars/radios could be sequenced in a controlled fashion. As previously mentioned, this platform also supports Two Way Time of Flight Range measurement. Consequently, it is possible to configure the system for ranging as well. This allows any platform to communication with any other platform, operate as a multi-mode radar and use the ranging capability to self-localize.

If the radar system has sufficient diversity, i.e. the target can be illuminated from many directions and many different elevations, it is also possible to image the target. Figure 8 [9] shows images of a variety of targets. All of these targets are shown on the same three dimensional scale with each axis spanning two meters.

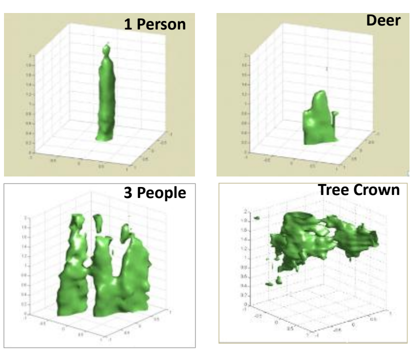


Figure 8. P400 radar images. (from the upper left): person, three people standing close together, the crown of short tree, a deer. All axis span 2 meters. Vertical grid spacing is 0.2m, horizontal grids spacing is 0.5m.

The quality of the image is a function of the resolution offered by the RF bandwidth. While the bandwidth of 1.4 GHz is not fine enough to produce detailed images, the gross features of the target can be readily distinguished.

Finally, preliminary experiments have indicated that it is also possible to analyze radar returns from a moving target and determine gait or other characteristic motions [10].

## V. Conclusion

It has been contended in this paper that the emergence of UWB as a ubiquitous radar has been limited not by the performance of the technology but by the availability of an inexpensive ASIC based device that can be used to demonstrate both utility and a path to low cost. It is further contended that the P400 chipset and OEM platform represent such a device. The P400 has been designed from ground up for maximum performance as a mono-, bi- and multi-static radar. Because regulators only allow the transmission of tiny amounts of power, it was necessary to take all steps possible to maximize receiver performance. Accordingly, this has been accomplished by relying on coherent processing; implementing the mixed signal circuits in Silicon Germanium; implementation of a rake receiver architecture and operation as a bi-static radar. The P400 achieves 1.4 GHz of RF bandwidth. This bandwidth provides the resolution to resolve clutter and to operate in difficult environments. Its dual receiver architecture allows the generation of high quality radar scans in a minimum of time, allows operation as a radio and enables bi-static radar operation. Because the platform can be used as a multimode radar as well as a communications platform and a ranging system, it should be useful in applications that require fused system capabilities.

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