Ultra-Wideband: A Tool for Teaching Undergraduates

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***Abstract* - This paper describes an Ultra-Wideband (UWB) platform, its capabilities and advantages relative to under-graduate education. To date, UWB has demonstrated its value in commercial applications and as a research tool. This paper proposes that it is also an excellent tool for teaching RF propagation, radar, communications, and range measurement.**

***Index Terms*—Ultra-Wideband, undergraduate education, student projects, electromagnetics, SAR Radar, navigation without GPS, robotics**

I. Introduction

It can be very difficult to teach radio and electromagnetics to undergraduates. There is a large gap between the theoretical teachings of Maxwell and the practical limitations of laboratory exercises. High frequency test equipment is frequently too complex, expensive and delicate to consider using in a student lab. Electrical engineering students frequently lack a physical basis for intuition which other engineering students arrive with. For example, mechanical engineers can understand stress by bending their pencils. Chemists learn about solvents and solutions each time they add sugar to coffee. Hydraulic engineers build their intuition each time they observe rain falling and flowing into streams.

The question then becomes, how does one build the intuition of an electrical engineer such that he can more easily understand something as invisible as radio waves? It is suggested that Ultra-Wideband could be such a tool. The impulse basis of the technology fits well with the study and mathematics of impulse responses. The hardware is stable, easy to use and visual. It allows RF to be observed in real time as it moves through space. UWB is a high performance technology and permits the execution of extremely sophisticated experiments with a minimum of guidance.

This paper will describe a suitable UWB platform, summarize the advantages relative to undergraduate educations and summarize the practical results accomplished to date.

II. Description of the Platform

This section describes a representative platform, explains the practical value of achieving large RF bandwidths and concludes with a description of a student-friendly interface.

A. *The UWB Platform*

The platform in question is a Time Domain P400 UWB platform [1]. This platform (Fig.1) has been designed to coherently transmit and receive UltraWideband RF pulses. The transmissions have a nominal pulse repetition rate of 10 MHz (other rates are possible). Each transmitted impulse has a center frequency of 4 GHz and achieves approximately 1 GHz of RF bandwidth. A representative pulse is shown in Fig. 2. Two versions are available, one is compliant with the American FCC Part 15 regulations and the second is compliant with the European CE/ETSI 302 065 rules.

Fig. 1. P400 shown with supply, battery and chargers.

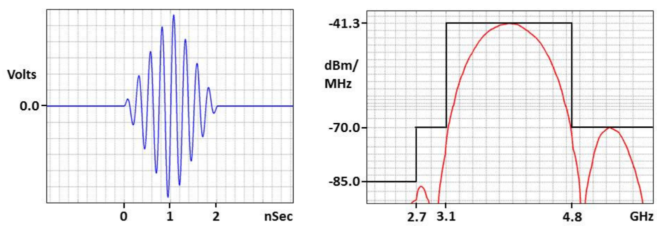

Fig. 2. Nominal pulse in frequency (l) and time domains (r) for EU low band.

The pulses can be modulated by inverting the pulse. Modulation provides the opportunity to transmit data and to define independent communications channels.

The UWB pulse transmission circuitry is relatively simple with pulses being transmitted based on timing signals which are have a resolution of 2ps and an accuracy of less than 5ps.

UWB receiver is more complex in that it has been implemented as two independent receiver channels. This architecture is key to the performance of the system because it allows one channel to synchronize and lock to the received transmissions while the second channel measures the signal strength of the received signal as a function of time relative to the received lock point.

The timing accuracy is also important because it enables fully coherent transmissions. In other words, the energy of a single bit can be spread over many transmitted pulses and on reception the energy of the several pulses can be summed to recreate the original bit. This technique allows the user to trade increased transmission time for increased Signal to Noise Ratio (SNR). More specifically, this means that each time the number of pulses in a bit symbol is doubled, the SNR of the received signal will also double. This is particularly important because regulations limit operation to transmit powers of only a few 10s of microwatts. At such trivial power levels, coherent integration allows operation as radar to a few 10s of meters and ranging/communications to a few 100s of meters.

B. The value of bandwidth

As previously mentioned the UWB platform achieves approximately 1 GHz of RF bandwidth. This bandwidth is important for several reasons:

- Bandwidth allows the system to easily resolve multipath. As a result, the system operates well inside buildings and other highly reflective environments such as steel containers, ships, screen rooms, etc.
- Bandwidth allows operation as a high performance radar. The platform performance (with the exception of range) is comparable to that of high performance military radars.
- Bandwidth allows operation as a high resolution range measurement system. System accuracy is on the order of a few centimeters and under certain conditions, some user have reported accuracies of 0.5cm. Not only can the first arriving energy be easily identified from multipath, but the characteristics of the received energy can be analyzed to determining if the signal was from a direct path or non-line of sight.

C. Student Friendly Interface

The P400 is controlled through a set of well-defined commands that are documented in an Application Programming Interface (API). This interface is typically operated over a USB or serial interface. A Graphic User Interface (GUI) is provided that allows operation on a Windows or Linux-based PC. For users interested in developing specific applications, sample C and MATLAB code is available.

The GUI allows the user to define the operating configuration of the platform and to display and log received waveforms. An example of a captured waveform scan is shown in Fig. 3.

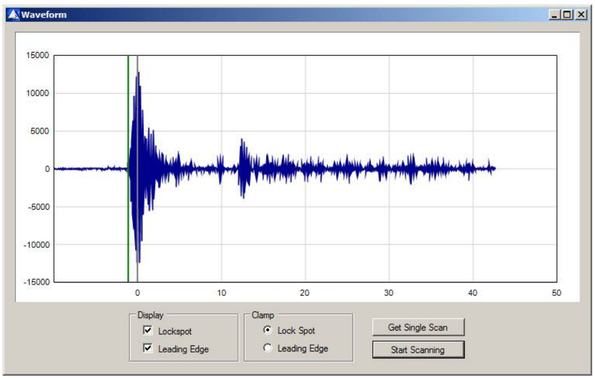

Fig. 3. GUI screen capture illustrating typical channel impulse response/bi-static radar scan.

This ability to capture waveform scans is most useful as the measurement represents the impulse response of the environment. This waveform can be used in a number of different ways. A communications engineer could use the GUI to collect a set of these waveforms from a given area and then use these measurements to construct a channel model of the measured environment. A radar engineer would recognize this waveform as a bi-static radar return and would use a set of these waveforms to define the location of fixed objects or detect, locate and track targets as they moved through an environment. An instrumentation engineer might look at the first arriving energy (as indicated by the green line in Fig. 3) and then use this information to measure the distance between transmitter and receiver.

In point of fact, four different GUIs have been developed for use with the platform: one supports operation as a Monostatic radar, one allows operation as a bi/multistatic radar or channel impulse measurement system, one uses Two Way Time of Flight to provide inter-radio range measurements with an accuracy of a centimeter, the final GUI allows operation of a network of ranging radios based on a random access ALOHA protocol or time slot based TDMA protocol.

III. Capabilities Consistent with Undergraduate Needs

This section discusses the ways in which the capabilities of UWB platforms are consistent with the needs of undergraduates. More specifically:

- The equipment is well matched to a student’s skill and typical environments in which it will be operated.
- The software interface and supplemental processing capabilities enable investigation of more complex problems.
- The equipment’s ability to support simultaneously ranging, radar and communications makes it useful for interdisciplinary projects such as robotics.

A. Platforms match students technical level

First, the equipment is safe to operation. While most radars have transmit power between Watts and kiloWatts, UWB platforms are limited to microwatts and, under special conditions, a maximum of only a few milliWatts.

Second, the sample GUI is easy to learn. Within a half hour a student can master operation of platform. This includes configuration of the platform as well as display and logging of all received waveforms. Logged files are stored in .csv format and can be easily processed with MATLAB, XCEL or C.

Third, because each platform can be operated on different channels, several systems can be operated simultaneously in the same area with negligible channel to channel interference.

Fourth, the platforms are not toys. They achieve significant bandwidth allowing meaningful experiments in complex environments.

Fifth, as long as platforms are separated from each other and from strong reflectors by few meters, the units are effectively in anechoic chambers. Fig. 4 illustrates a typical test set up with two units mounted on tripods and separated by 1.5 meters.

Fig. 4. Typical on air set up. Performance roughly equivalent to operation in an anechoic chamber.

Figure 5 shows typical received waveforms when operating over antennas (top) and operating on cables (bottom). To a first approximation they are the same. The area indicated by the arrow shows a difference which is most likely attributable to a multipath reflection from either the battery or the tripod.

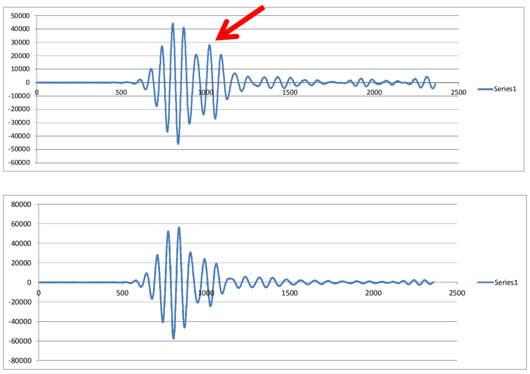

Fig. 5. Response on air (top) vs. over cables (bottom). Arrow indicates likely multipath reflection. (Scale is relative signal strength vs. time in increments of 61ps.)

This insensitivity to operation in close quarters means that it is possible to measure antenna beam patterns, measure the effect of polarization, generate link budgets and validate radar range equations in a typical university laboratory rather than in anechoic chambers or test ranges.

Finally, the equipment is rugged and tolerant to abuse. If it is somehow broken, it is typically repairable. If destroyed or lost, it can be inexpensively replaced. Cost is comparable to that of a midrange signal generator and in any event is only a small fraction of the cost of the multi-gigaHertz scopes, spectrum analyzers or high speed probes that one typically finds in an RF lab.

B. Interface and Sample Code Enables Higher Order Experiments.

The P400 platform is excellent at displaying waveforms in real time. This is very useful for demonstrating different phenomenon and building an intuitive feel for RF. But the real value lies in the ability of the system to store captured waveforms. These waveforms are rich in information and can be post processed to demonstrate a number of important functional modes. For example, radar I and Q data can be used to demonstrate operation as a Doppler radar or as a synthetic aperture radar. Waveforms (and specifically multipath) can be processed to determine channel impulse response. Monostatic, bistatic and multistatic radars can be implemented and targets can be detected, located, tracked, imaged and classified. Network performance can be demonstrated and performance quantified.

To aide in the analysis of this data, sample code is provided. Not only does the code illustrate interesting behavior but the code also contains subroutines which perform useful functions such as opening and parsing of files. This code can be copied and modified for inclusion into programs developed by students. Five examples will be discussed.

1) Sample MATLAB for converting captured waveforms into SNR as a function of distance.

A typical experiment might be focused on determining the range performance of a radio. To do this one could use the GUI to collect waveforms as the distance between two P400 radios was increased. Since the radios measure distance and logs waveforms it is an easy matter to compute and plot the signal strength, noise and SNR as a function of range (Fig.6). Such plots can be used to validate link budgets and observe destructive and constructive Fresnel effects.

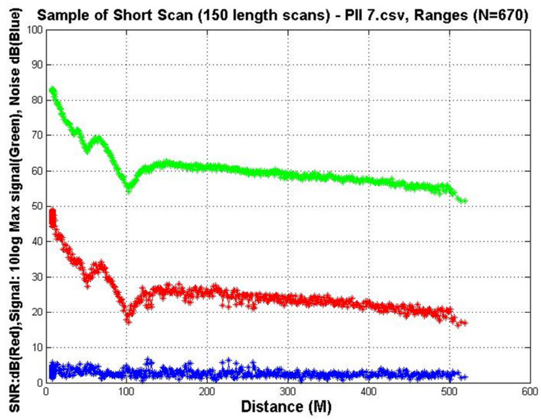

Fig. 6. Sample code allows plotting of range vs Signal strength, SNR and noise.

2) Sample MATLAB for converting Monostatic radar returns into motion filtered waterfall plots

The Radar GUI allows the user to view instantaneous radar returns and motion filtered results. These can be viewed and logged. Sample code is provided with opens log files, then calculates and plots motion filtered results in a waterfall format. An example is shown below in Fig.7. This code can be easily modified to evaluate the performance of different motion filters.

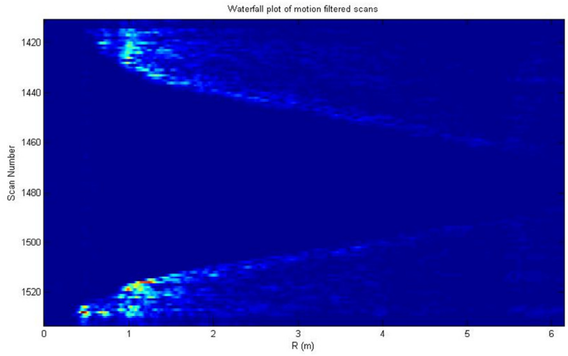

Fig. 7. Radar waterfall graph

3) Sample MATLAB for Real-time Doppler Signal Processing

While the GUI can collect and display both raw waveforms and motion filtered results, it is not set up to display Doppler results. Sample MATLAB has been developed to interface directly to the P400 such that the MATLAB code can drive the radar directly, collect data, compute I and Q data and then plot Doppler result in real time. In the example below, the author (the large red spot) is seen walking toward the target.

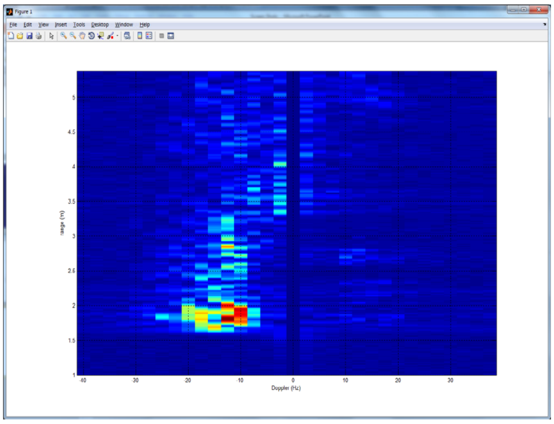

Fig. 8. Target approaching the radar.

4) Sample MATLAB for converting waveforms into channel impulse responses.

A MATLAB script has been provided to convert waveforms captured by the GUI into Channel Impulse Responses. An example is shown in Figure 9. The top graph shows the original waveform (upper graph in blue), the Impulse Response as computed using the CLEAN algorithm (bottom) and, as a check, a reconstructed waveform using a template waveform and the channel impulse response (upper graph in red).

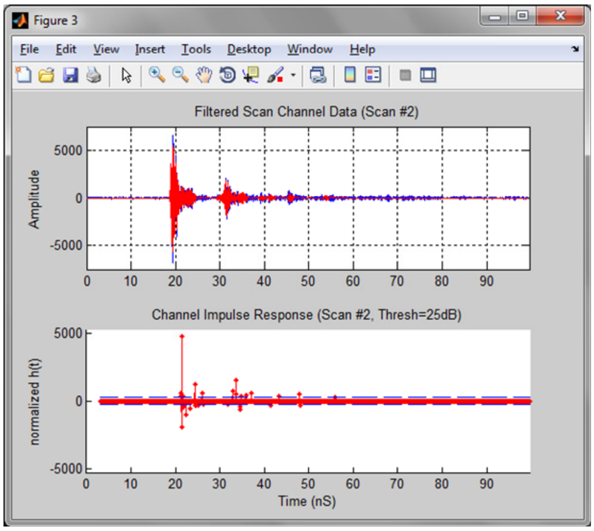

Fig. 9. Converting captured waveforms into channel impulse response

5) Samples C and MATLAB for driving the radio directly.

While the GUIs are excellent tools for controlling and monitoring UWB Platforms, there are times when the user will want to control the units directly either with MATLAB scripts or via a single board computer. To enable such control sample C and MATLAB have been developed which illustrate interface through serial, USB and Ethernet connections.

C. Interdisciplinary projects

The UWB platforms are all capable of acting as a multi-mode radar, a communications system, a range measurement system and a network. This flexibility makes it an excellent tool for team based applications such as robotic. Besides the usual mechanical, electrical and control aspects of robot construction, UWB adds the possibility of including radar sensing (and signal analysis), range measurement, the calculation of 3-D position and data transfer. These new features increase system complexity and allow students to investigate more sophisticated problems.

For example Chalmers University (Sweden) uses the ranging capability to study operation of the highway of the future. Students build robots and control their position relative to each other and a virtual highway.

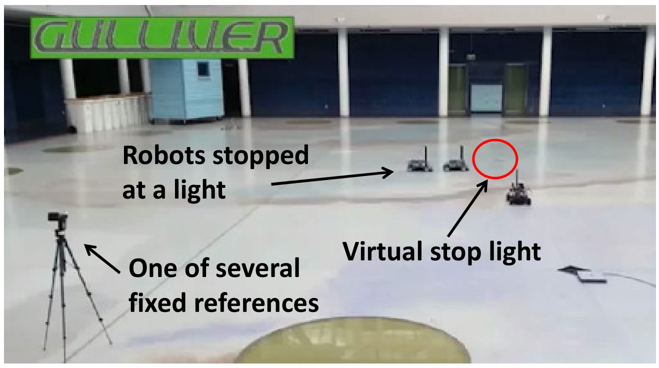

Fig. 9. Chalmers University Highway of the Future project.

IV. Progress to Date

Currently, more than fifty universities worldwide are using these platforms. Most of the platforms are intended specifically or primarily for post graduate research projects. However, several universities are developing laboratory experiments specifically aimed at undergraduate courses. Most notably, the University of Alabama-Huntsville (UAH) has received a National Science Foundation grant to develop an entire curriculum of experiments using this equipment. This project will focus on using UWB to illustrate various signal processing techniques and will complete in approximately one year. Two other universities are in the process of developing experiments for specific undergraduate courses and several others are considering similar efforts.

To date there have been several accomplishments. UAH has used UWB in several undergraduate projects. For example, these projects include a radar sensor for guiding the blind and a personal ranging measurement system. A particularly successful project [2, 3] was a semester long project in which a team of three 4^{th} year students built a SAR using a UWB radar, two directional antennas, a worm gear drive and stepper motor. They used it to implement and characterize a SAR. To highlight operation, the students stacked empty cans to form the university letters (U-A-H) and then imaged the target (Fig.10). They then placed a wooden wall between the radar and the target and demonstrated a through wall imaging radar. For this effort they took second place in a regional competition.

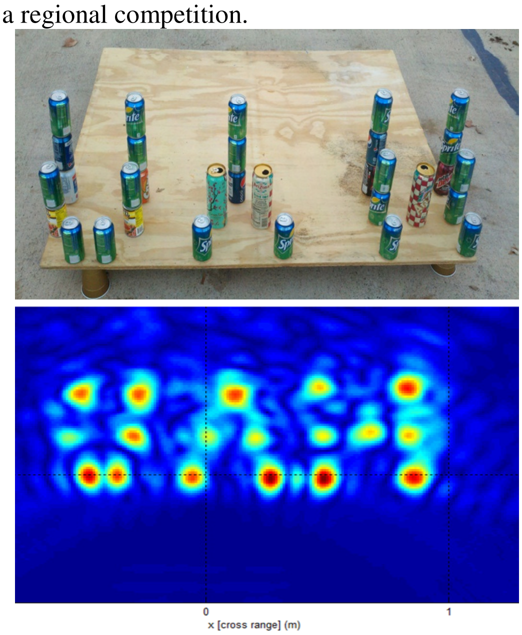

Fig. 10. SAR images of an array of soda cans

Time Domain Doppler is contributing to two ways. First, we have developed a few experiments, one of which involves analyzing the Doppler radar return of a swinging pendulum [4]. The plot of time vs. velocity for a given range shown in Fig.11 illustrates the motion of the pendulum. At a fixed distance one can see the target moving toward and away from the radar, the decay of the length of the pendulum arc be measured, and that the period of a pendulum remains constant independent of the length of the arc thereby confirming Galileo's famous observation.

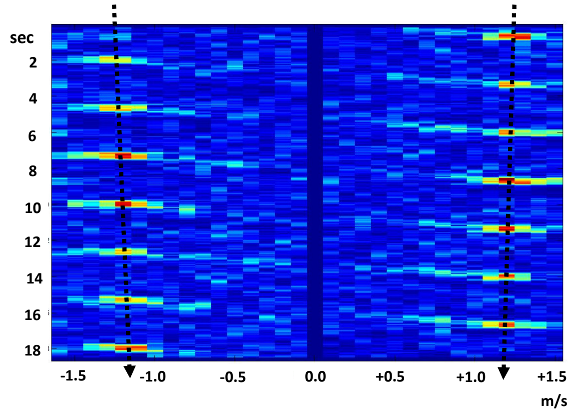

Fig. 11. Doppler processing of radar return of a pendulum in motion.

Second, Time Domain is continuing to develop and provide example C and MATLAB sample code. We are also interested in expanding the capabilities of the equipment so that we can support new capabilities or new classes of experiments.

Other universities are developing specific experiments for use in a more general course. For example, the University of Texas (Austin) has developed an experiment which illustrates the relationship between a communications propagation channel and delay spread [5].

V. Research Efforts

While the focus of this paper has been the use of UWB as an educational tool, it should be noted that this is a secondary use. One of the primary uses of the equipment to date has been in post graduate research for which it has proven to be a valuable tool. For example, the equipment has been used to develop network protocols, enable robots to successfully navigate, and image a variety of targets [6,7].

VI. Conclusion

In conclusion, it has been argued that UWB is a practical and useful tool for introducing undergraduates to the fields of RF, signal propagation, radar and signal processing. It also makes projects like robotics more powerful.

UWB makes RF waveforms visible and easy to work with. Well-crafted experiments can take advantage of this characteristic to make RF behavior more intuitive and less theoretical. However, creating a set of experiments which can be completed by an undergraduate in a few hours and which also illustrates an important principal is a surprisingly time consuming task. It is the author's believe that if several universities developed and shared a few experiments, then all universities would have access to many experiments. To that end, Time Domain is trying to develop communications channels through which these experiments can be encouraged and shared. Like minded researchers are encouraged to contact the author directly.

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