Recent Advances in Ultra Wideband Radar and Ranging Systems

Invited Paper

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***Abstract* – This invited paper describes recent advances in short pulse electromagnetics as applied to Ultra Wideband (UWB) radar and precision ranging. UWB sensors designed for perimeter intrusion detection, obstacle and collision avoidance and industrial safety applications will be described. The design of a Part 15 compliant, UWB radar development kit is also discussed.**

***Index Terms* – Ultra wideband, Radar, Spread spectrum radar, Electromagnetic measurements**

I. INTRODUCTION

The application of short pulse electromagnetics (UWB) to radar systems has a long history of development [1-3]. This invited paper discusses several recent UWB radar and (cooperative) ranging systems developed for various Government and commercial applications. In addition to exploiting the inherent advantages of short pulse radar for precision distance measurements, these unique sensors are seen to leverage UWB's advantages in energy efficiency (e.g., unattended, battery-operated sensors) and reliable operation in multipath and clutter.

II. UWB PERIMETER INTRUSION DETECTION RADAR

Developed for the U.S. Government, this radar sensor provides an extremely low power, perimeter detection and target identification capability. The radar utilizes UWB technology for superb clutter rejection as well as for extended-life battery operation. Operationally, the intrusion detection radar is used to monitor the traffic of vehicles and personnel in remote locations by acting as a cueing device for an infrared (IR) video imaging sensor (see Figure 1 below).

Fig. 2. UWB Radar shown in Field Deployment.
(Radar is black unit to the right of rectangular control/battery unit)

The radar detects an intrusion with a single sample of the environment while consuming less than 6 milliJoules of battery energy per sampling event. The radar sensor operates off of two standard AA batteries. Utilizing this low power UWB sensor as a trigger device for the much higher power consumption video camera system provides two major advantages, namely a significant reduction in the amount of video imagery to be post-processed and extended life, unattended operation on moderate capacity batteries. The field-of-views (FOVs) for both radar and IR camera were matched and sensor data relayed wirelessly from the unit only if the image met certain detection criteria. In this fashion, the communications network and end user are not overwhelmed with a large volume of raw sensor data.

The intrusion system radar hardware is illustrated in Figure 2, where the UWB receiver/processor and transmitter circuit cards are mounted behind a dual patch antenna array. The radar electronics package is mounted in an all-weather chassis for field deployment.

Fig. 2. UWB Perimeter Intrusion Detection Sensor Hardware.

A system block diagram of the UWB radar sensor is shown in Figure 3.

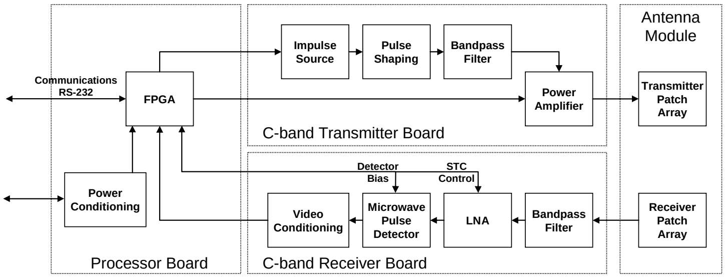


Fig. 3. Block Diagram of the Perimeter Intrusion Detection Radar.

Radar operational hardware consists of three major system components:

(a) Antenna module consisting of a pair of 15 dBi gain antennas (transmit and receive), each with a 16 x 45 degree field of view;

(b) C-Band receiver/signal processing module; and,

(c) C-band UWB transmitter module.

The antenna module consists of two C-band antenna arrays, one for transmit and the second for receive. The system's operational (-3dB) frequency range is 6.0 to 6.4 GHz, with a -10dB bandwidth in excess of 1.25 GHz. Each array consists of an 8-element (4 x 2), wideband microstrip patch configuration to achieve the desired gain and directivity (i.e., to match that of the IR sensor optics). The antennas are spatially configured so as to provide low cross-coupling between receive/transmit array elements preventing blinding of the radar's near field range gates by the transmitter pulse.

All radar signal processing functions are performed in hardware within a single generic Field Programmable Gate Array (FPGA). After detection, the return signal from each transmit pulse is processed simultaneously within each of 512 range gate intervals [4]. In this fashion, multiple targets at varying ranges can be detected and processed with a minimal expenditure of both transmitter and signal processor energy. Returns from each range gate are digitized and, after N successive pulse transmissions, the highest quantization level that is exceeded at least M times (M<N) is assigned to the corresponding range gate. This 512-length vector is compared, element by element, to a clutter map which is stored in memory and initialized upon system start up to the zero vector [0,0,…,0]. If any element of the received vector exceeds, by some predetermined threshold, the corresponding range gate entry in the clutter map, a detection event is declared for that specific range gate. The clutter map is then updated using an autoregressive moving average of the previous clutter map contents and the current receive vector.

In order to minimize radar power consumption, the radar electronics are placed in a low standby current, sleep mode until wakened by a watchdog timer to perform a periodic sampling of the environment. The clutter map is stored in non-volatile memory and reloaded upon subsequent power-up. As a person, vehicle or other object moves into the radar's field of view, target presence is readily discerned from the comparison with the most recent clutter map information. If the target stops moving, it can be seen that its return will gradually disappear as it melts into the new clutter map. However, any subsequent motion creates a significant change in one or more range bins, creating a strong detection event. In operation, the system has demonstrated a sensitivity to detect a minivan in excess of 600 feet, a standing human target in excess of 450 feet and a crawling subject in excess of 300 feet. Each detection event consumes only 6 milliJoules of receiver/processor energy – only 3.5 nanoJoules of which is attributable to the transmitted pulse energy.

Table 1 summarizes the physical and performance characteristics of the UWB Perimeter Intrusion Detection Radar.

Table 1. UWB Perimeter Intrusion Radar Characteristics

RF Characteristics	Center Frequency	6.20 GHz
	Bandwidth	400 MHz (-3dB) 1250 MHz (-10 dB)
	Peak Power	+31 dBm
	Antenna Gain	15.0 dBi
	Antenna FOV	45 x 16 degrees
System Performance	Primary Power	1.0 W (7-33VDC)
	Detection Range	Offset + 512 feet (Offset 0/100 feet)
	Range Resolution	1 foot
	PRF	Selectable to 330 Hz
	Interface	RS232 115.2 kb/s
Physical Characteristics	Circuit Card Stack	2.25 x 3.5 x 1.38 inches with shield
	Dual Patch Antenna	5.25 x 6.30 x 0.17 inches
	Circuit Card Weight	90 grams
	Antenna Weight	160 grams
Demonstrated Detector Sensitivity	Human, Standing (6' tall)	450 feet
	Human, Crawling	300 feet
	Minivan	In excess of 600 feet

III. OBSTACLE AVOIDANCE RADAR

Developed under contract to the U.S. Army to provide an obstacle detection capability for unmanned aerial vehicles (UAVs), the UWB Obstacle Avoidance Radar (OAR) is an improved version of the previously described Perimeter Intrusion Detection radar. The unit is illustrated in Figure 4 below.

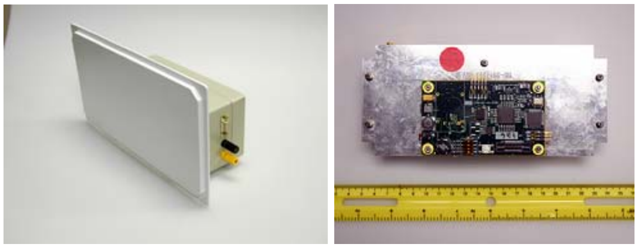


Figure 4. OAR UWB Radar
Antenna Module & Digital Processor

OAR utilizes a higher gain (17.5 dBi) C-band patch array and a higher peak power (+37 dBm) UWB transmitter. The minimum detectable signal (MDS) to the receiver/processor was also reduced by improving the system front end noise figure (low NF pHEMPT device) and reducing wideband detector noise pickup from the radar's digital electronics. These improvements resulted in an overall 10 dB gain in weak signal performance over the Intrusion Detection Radar design. With its greater sensitivity, OAR was able to detect overhead power lines, major problems for both manned (e.g., Medivac helicopters) and UAV flight, at ranges in excess of 300 feet.

An interesting experiment was performed with the radar, using it to capture the return from a Mallard duck flying low (6 feet) above the water surface. The return from the Mallard is shown in Figure 5, where detection is illustrated at a range of approximately 260 feet as the duck flew toward the radar. As seen, the detector output voltage is approximately 12 dB above the system noise floor. For reference, the radar cross section (RCS) of a duck is approximately -20 dB square meters (dBsm).

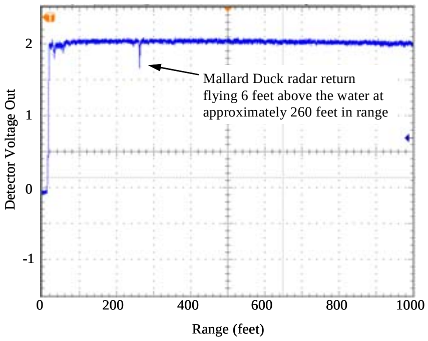


Figure 5. Screen capture of a mallard duck in flight using OAR

In this experiment, the duck was flying near the water surface which introduced an interesting multipath interference effect with the received signal. Figure 6 shows the four different possible signal paths from a UWB radar to a target. Note that, upon reflecting off the water surface, the signal changes polarity as a function of the incidence angle. For low grazing angles with a vertically polarized signal, the polarity shifts nearly 180 degrees upon reflection. These returns combine at the radar antenna.

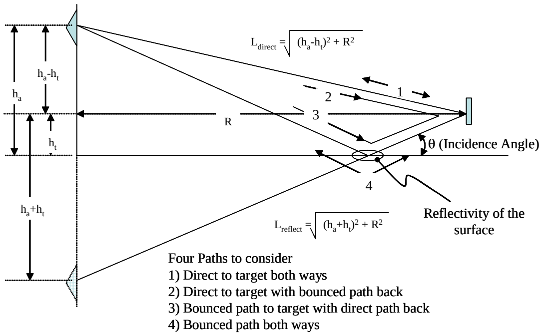


Figure 6. Ray Tracing of Radar Multipath from Target

In the above example, the radar antenna was approximately six feet above the lake surface, approximately the same height as that of the flying duck. The difference in path length between the multipath return and the direct path was thus approximately 8.4 cm, with the UWB pulse length approximately 75 cm. Mathematically combining the UWB pulse returns with the time delays and phase shifts produced by the path geometries, one obtains the result in Figure 7. Here, multipath gain/loss is plotted as a function of range to target. For this analysis, the lake surface was assumed to have perfect conductivity so that each ray added equally.

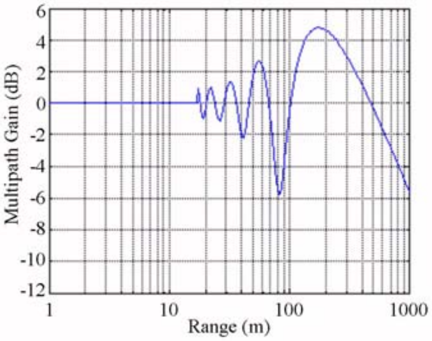


Fig. 7. Multipath Gain/Loss for 2m Antenna/Target Heights

As observed in Figure 7, multipath can provide both destructive and constructive interference effects. At a range of 260 feet (80m), for example, there is approximately 6 dB of destructive interference. This interference was observed on the scope as the duck flew toward the radar, with the signal magnitude fluctuating wildly during the entire approaching sequence. An additional source of fluctuations (unmodeled) resulted from the waves on the water surface that further scattered the multipath returns. Table 2 shows the approximate RCS at 6 GHz for various surface components of a small, 1 meter length, 3 meter wingspan, air vehicle. These values do not consider the contribution of the UAV engine or other electronic components. Manned aircraft, on the other hand, have radar cross sections that are significantly higher. For example, a typical (non-stealthy) aircraft that can fly at flight speeds of 250 knots will have a radar cross section approaching 10 to 20 dBsm. Table 3 provides the estimated detection range for OAR as a function of RCS.

Table 2. Estimated RCS of Small UAV at 6 GHz

UAV Component	Aspect	Radar Cross Section at 6 GHz
Body	Broadside	-1 dBsm
Nose / Tail	Nose / Tail	- 25 dBsm
Wings	Nose / Tail	- 10 dBsm
Propeller	Nose / Tail	- 7 dBsm
	Broadside	- 26 dBsm

Table 3. OAR Detection Range vs. RCS

RCS (dBsm)	Detection Range (ft)
-20	500
-10	890
0	1580
10	2820
20	5020

IV. RADEKL – AN FCC-COMPLIANT RADAR SYSTEM

In 2002, MSSI developed a portable, battery operated, radar sensor nicknamed “SPIDER”, for “Short Pulse

Intrusion Detection Radar”, which was the first UWB system-level product to receive FCC approval under the new Part 15 Subpart F regulations. Originally developed under a DARPA contract for micro air vehicle collision and obstacle avoidance applications [5], the FCC-certified version of this sensor operated in the 6020-6699 MHz band under Subpart F Part 15.511 “Technical requirements for surveillance systems” [6]. Operation under 15.511, however, is limited to fixed surveillance systems operated by law enforcement, fire or emergency rescue organizations or by manufacturers licensees, petroleum licensees or power licensees as defined in FCC Section 90.7 (“Part 90” users).

In March 2005, the FCC significantly expanded the application space for UWB equipment that operates in the Part 15.205 non-restricted band segment from 5925-7250 MHz by creating Part 15.250 for general UWB applications [7]. While the original SPIDER radar sensor could have been recertified for use under 15.250, significant advances had been made in UWB technology since early 2002, and a new radar design incorporating these advances was developed. The new, Part 15.250 compliant, radar sensor is called RADEKL (see Figure 8), “Radar Developers’ Kit ‘Lite’”, as it is designed specifically for radar applications engineers.

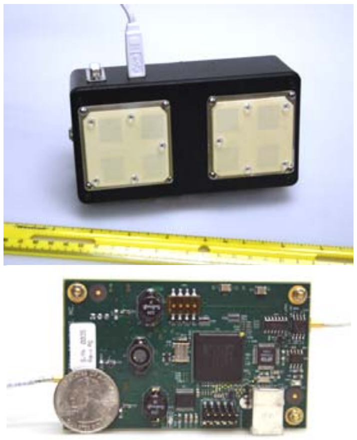


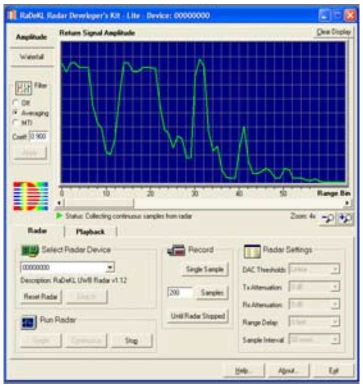
Figure 8. RADEKL UWB Radar Sensor with Single Board Design (antenna radome removed)

Except for its lower radiated power level, and hence more limited range, RADEKL is an advanced version of both the Perimeter Intrusion Detection and OAR radars described above. The radar utilizes 256 range bins, each having 30 cm range resolution and 5-bit amplitude return quantization. The detection range to a person was approximately 60 feet.

RADEKL uses a UWB transmitter design which was taken from MSSI’s FCC-certified, real time location system (RTLS) tags. The transmitter electronics is mounted on a 7 x 10 mm thick film ceramic substrate, illustrated in Figure 9. Interestingly, given the patch array antenna gain of approximately +11 dBi, the output of this tiny C-band transmitter needs to be further attenuated in order to meet the FCC peak power density of 0 dBm/50 MHz.

Figure 9. C-band Thick Film Ceramic Transmitter Chip

The complete radar development environment includes UWB hardware, supporting software drivers and a user interface application (see Figure 10) which permits viewing of the radar return data and data logging for additional return signal post processing.



Status: Collecting continuous samples from radar

Filter: ○ Off ● Averaging ○ MTI

Coeff: 0.900

00000000

Description: RaDeKL UWB Radar v1.12

200 Samples

Figure 10. RADEKL Graphical User Interface (GUI) (Return through multiple walls in office building)

Table 4. RADEKL Radar Characteristics

RF Characteristics	Frequency	6.0 – 6.6 GHz (-10 dB)
	Bandwidth	400 MHz (-3dB)
	Peak EIRP (with antenna)	0 dBm/50 MHz (Variable to -25 dBm/50 MHz)
	Antenna Gain	11.0 dBi
	Antenna FOV	40 x 40 degrees
System Performance	Primary Power	1.2 W (12VDC)
	Receiver Sensitivity	-75 dBm for 10 dB S/N
	Detection Range	345.6 m (max) (1152 ns)
	STC Control	40 dB
	Range Resolution	1 foot 256 Range Bins
	Interface	USB 2.0 Windows XP
Physical Characteristics	Sensor	150 x 83 x 62 mm
	Weight	490 grams
Demonstrated Detector Sensitivity	Human, Standing (6’)	60 feet

V. UWB RANGE MEASURING RADIOS

The last system design to be described also utilizes UWB technology for precise range measurements. However, unlike the previous examples, ranging is accomplished cooperatively by measuring the round trip time of flight between two UWB transceivers. The system is similar in concept to a transponder-based ranging system [8] originally developed for DARPA to track soldiers in GPS-denied urban environments. The present Ranging Radio system was developed for the U.S. Army as a means for preventing soldier fratricide by providing accurate and reliable situational awareness.

The ranging radios are illustrated in Figure 11, together with an inside view of the single board design.

Figure 11. Ranging Radios with Single Board UWB Transceiver Design

As shown, the ranging radios consist of a single circuit card containing both UWB RF and digital timing/processing electronics, and a wideband omnidirectional antenna. The system operates at C-band with an instantaneous -10dB bandwidth of approximately 500 MHz.

Range measurements are made within the receiver to a one nanosecond precision utilizing a high-speed tunnel diode detector. With sample averaging, however, a range resolution of approximately 1 inch has been demonstrated.

The Ranging Radio architecture is event driven, with each radio only transmitting when commanded to do so either by direct user intervention (console mode via USB) or by wireless request from another radio. All commands and responses to commands are able to be routed through multiple radios to address the hidden node problem. Commands include Range, Discover, Read Memory and Write Memory.

The Range command initiates a two-way communications between two radios on the network to determine the round trip time of flight, and hence distance, between the radios. Up to 256 range measurements can be performed with a single command, with each measurement taking approximately 200 microseconds to complete. The Discover command instructs the destination radio to report all other radios that it can communicate with having the same group ID. (Multiple radio groups can operate together.) Read Memory instructs a Ranging Radio to read a specific range of addresses in user memory, whereas Write Memory instructs the radio to write to a range of addresses. User memory on each unit consists of an array of 512 x 8-bits and is available to pass messages or small amounts of data between radios. In a recent implementation, user memory was used to store digitized voice data, permitting the radios to operate as conventional walkie-talkies in addition to the ranging functionality. Windows drivers are provided to interface a computer to the ranging radio for end user software development.

To perform a range measurement, a Ranging Radio transmits a packet consisting of a synchronization preamble and header. The header contains the Range command with the address of the radio which is requested to respond to the packet. Upon transmission of the packet, the originating radio resets is main counter, establishing a local time-zero reference. If a Ranging Radio receives a Range request addressed to it, it records the fine time (to 1 nanosecond resolution) at which it received the originating packet (relative to its system clock which generates the packet stream), and then replies with its own packet that includes this fine time information in the header. The originating radio receives the ranging packet from the destination radio, records its fine time and latches its main counter. The range value is then calculated and recorded, utilizing the fine time information to compensate for the difference in time-of-arrival at the destination receiver and the system clock epoch timing which generates the packet data stream.

The Ranging Radios were tested at the U.S. Army's CERDEC facilities in Ft. Monmouth, NJ to assess the effects that propagation through various wall materials has on range measurement accuracy. A variety of "standard", 1-foot thick walls of various construction (adobe, brick, cinderblock, steel-reinforced concrete, etc.) were used in the testing. As expected, range measurements were elongated as the signal passed through various wall materials, with the amount of elongation directly proportional to the amount of material traversed (e.g., propagation at oblique angles to the wall resulted in more material, and hence, increased delay and range error). Range offsets varied from one to three feet in most building materials, and as much as three to five feet in propagation through steel-reinforced concrete. The former effects were likely due simply to the dielectric properties of the wall medium, where the speed of light is slowed in the wall material. In the case of the steel-reinforced concrete, however, a notable signal loss was also observed. As leading edge pulse detection was employed in the receiver electronics, it is believed that the weaker signal strength resulted in more ambiguity as to the position of the leading edge.

Operating at Part 15 levels with omni-directional antennas (as illustrated in Figure 10), the radios have a line-of-sight range in excess of 50 meters. With a directional antenna on receive, link ranges in excess of 200 meters have been obtained. For the Army, higher power transmitter options have been tested with line-of-sight ranges in excess of 1,600 meters using omni-directional antennas and with both transponders placed on the ground. With statistical averaging, range resolutions to better than 3 cm have been achieved. The latest design (see Figure 12) consists of a small 96 x 59 x 20 mm module weighing 86 grams. The antenna and radome weigh in at 20 grams. Power requirements for the module are 0.8W at 3 to 5 Volts. Either an RS232 or USB data interface can be used.

Figure 12: UWB Ranging Radio Module

Range measurement radios are ideal for positioning applications where GPS is not available (e.g., indoors, underground or in cluttered environments) or in situations where an affordable GPS solution does not provide the required positional accuracy. For example, a Real Time Kinetic (RTK) GPS receiver system, which can provide inch-level location accuracy, can cost upwards of $25,000. Additionally, RTK GPS receivers require clear, open sky, access to the horizon. If a building, high power line or even a streetlight post is in a GPS satellite’s propagation path to the remote receiver, this can cause a multipath reflection which can create location errors. Range measurement radios, on the other hand, perform the equivalent accuracy of expensive GPS solutions at a fraction of the cost and are independent of GPS receiver radio link multipath limitations.

End user applications have included industrial safety, situational awareness, localization in GPS-denied environments, tracking for robotic navigation, non line-of-sight surveying and network security (i.e., network access in controlled environments). Since the Ranging Radios can communicate their inter-node distances across a network of such devices, even through intervening walls and obstructions, they have immediate applicability to First Responder rescue.

VI. CONCLUSION

This invited paper has summarized some recent developments in short pulse electromagnetics as applied to ultra wideband radar and ranging systems. Novel C-band UWB products for intrusion detection, obstacle and collision avoidance and ranging have been described, together with an unique Part 15 radar device for general purpose applications and experimentation.

The latest FCC regulations for ultra wideband [7] now permit a wide range of radar and sensor applications in the 5925-7250 MHz, 16.2 – 17.7 GHz and 23.12 – 29.0 GHz bands, with the two upper (millimeter wave) bands expressly limited to vehicular radar applications. The 5925-7250 MHz segment (Part 15.250), where all of the systems described in this paper have been designed to operate, appears to be of particular commercial interest.

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